UNIVERSITY OF ALBERTA

# Context Sensitivity

CMPUT 416/500
Foundations of Program Analysis

Karim Ali
@karimhamdanali

# Previously

- Inter-Procedural Data-Flow
- Inherited vs Synthesized Analysis Info
- Caller-Callee Relationships
- Valid/Invalid Paths
- Staircase of Calls and Returns
- Demand-Driven Analysis
- Types of Contexts
- Important Language Features

How can we conduct context-sensitive analyses?

# Method Cloning

# Method Cloning

```
int i = 0;
int j = inc(i);
int k = inc(j);
```

# Method Cloning

```
int inc(x){
  int y = x+1;
  return y;
}
```

```
int i = 0;
int j = inc(i);
int k = inc(j);
```

# Method Cloning

```
int inc1(x){
  int y = x+1;
  return y;
}

int inc2(x){
  int y = x+1;
  return y;
}
```

```
int i = 0;
int j = inc1(i);
int k = inc2(j);
```

# Method Cloning

- ✗ Inefficient: too many copies for real programs
- ✗ Expensive operation
- ✗ Recursion!
- ✓ Yet simple and easy to understand

```
int inc1(x){
  int y = x+1;
  return y;
}

int inc2(x){
  int y = x+1;
  return y;
}

int i = 0;
int j = inc1(i);
int k = inc2(j);
```

# Method Inlining

# Method Inlining

```
int i = 0;
int j = inc(i);
int k = inc(j);
```

# Method Inlining

```
int inc(x){
  int y = x+1;
  return y;
}
```

```
int i = 0;
int j = inc(i);
int k = inc(j);
```

# Method Inlining

```
int inc(x){
  int y = x+1;
  return y;
}
```

```
int i = 0;

int x1 = i;
int y1 = x1+1;
int j = y1;

int k = inc(j);
```

# Method Inlining

```
int i = 0;

int x1 = i;
int y1 = x1+1;
int j = y1;

int x2 = j;
int y2 = x2+1;
int k = y2;
```

# Method Inlining

- ✗ Lost procedure abstraction
- ✗ Exponential blow-up
- ✗ Recursion!
- ✓ One procedure => intra-procedural

```
int i = 0;

int x1 = i;
int y1 = x1+1;
int j = y1;

int x2 = j;
int y2 = x2+1;
int k = y2;
```

… so what do we do?

# Context Sensitivity

# Context Sensitivity

Call Strings

Functional

# Context Sensitivity

Call Strings

Functional

- Extend facts with context strings
- Re-evaluate procedure for each extension

✓ Universally applicable

✗ Recursion!

# Context Sensitivity

## Call Strings

- Extend facts with context strings
- Re-evaluate procedure for each extension

✓ Universally applicable

✗ Recursion!

## Functional

- Compute summary function per callee
- Apply summary to each context

✓ Recursion!

✗ Not always applicable

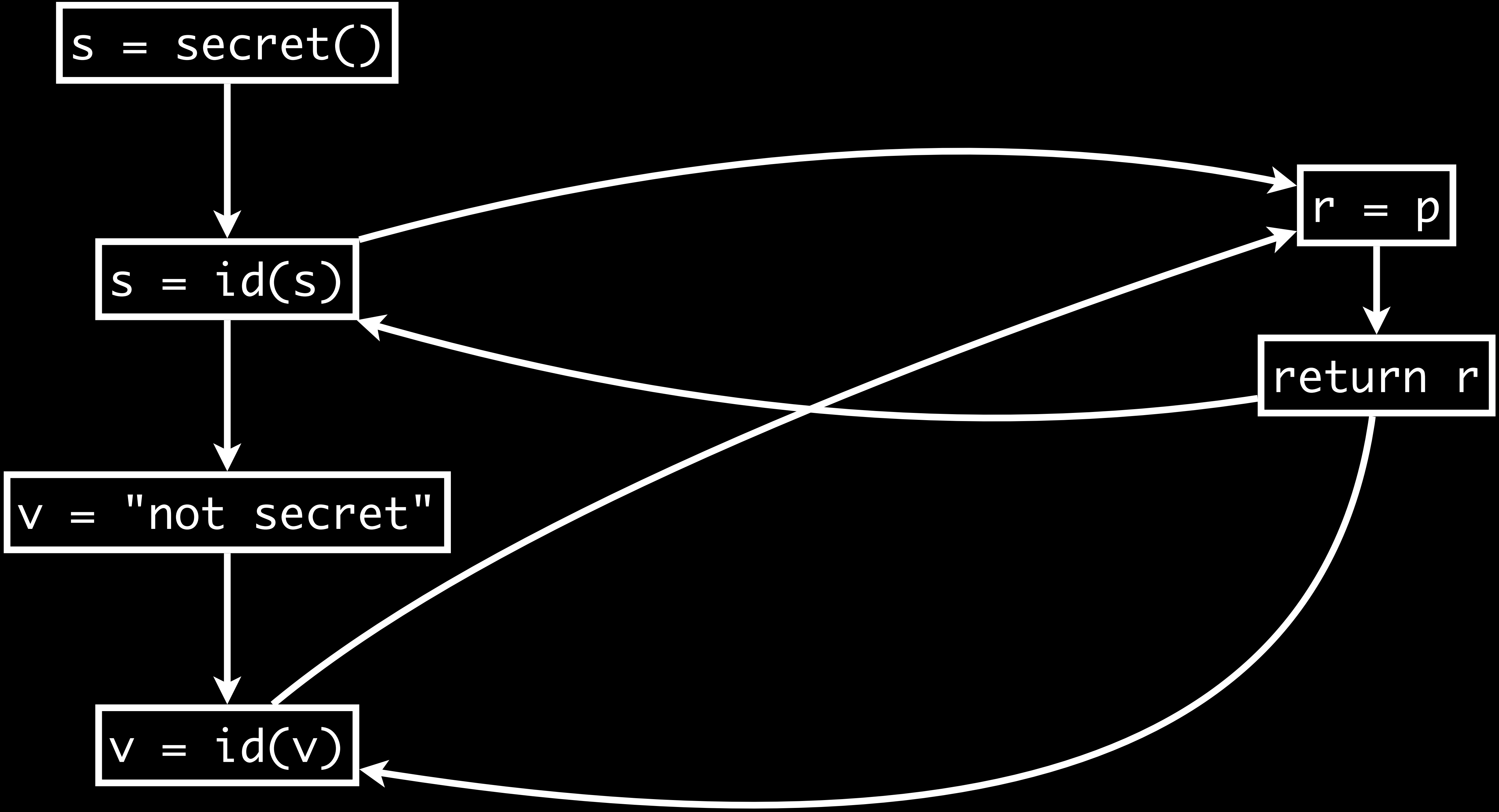
# Call Strings

# Call Strings

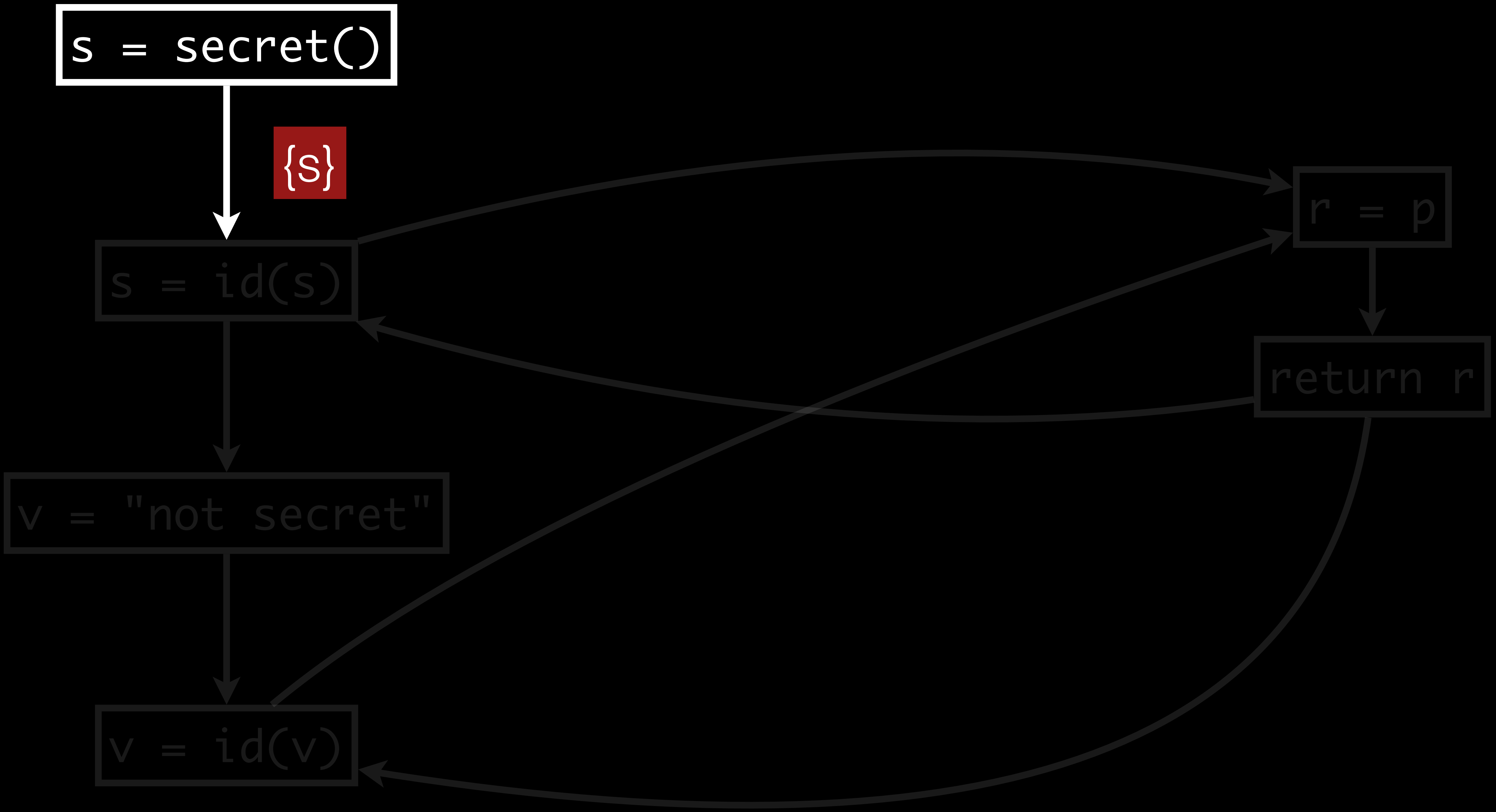
```
main(){
  s = secret();
  s = id(s);
  v = "not secret";
  v = id(v);
}
```

```
id(p){
  r = p;
  return r;
}
```

# Call Strings


```
s = secret()
```
```
s = id(s)
```
```
v = "not secret"
```
```
v = id(v)
```
```
r = p
```
```
return r
```

# Call Strings



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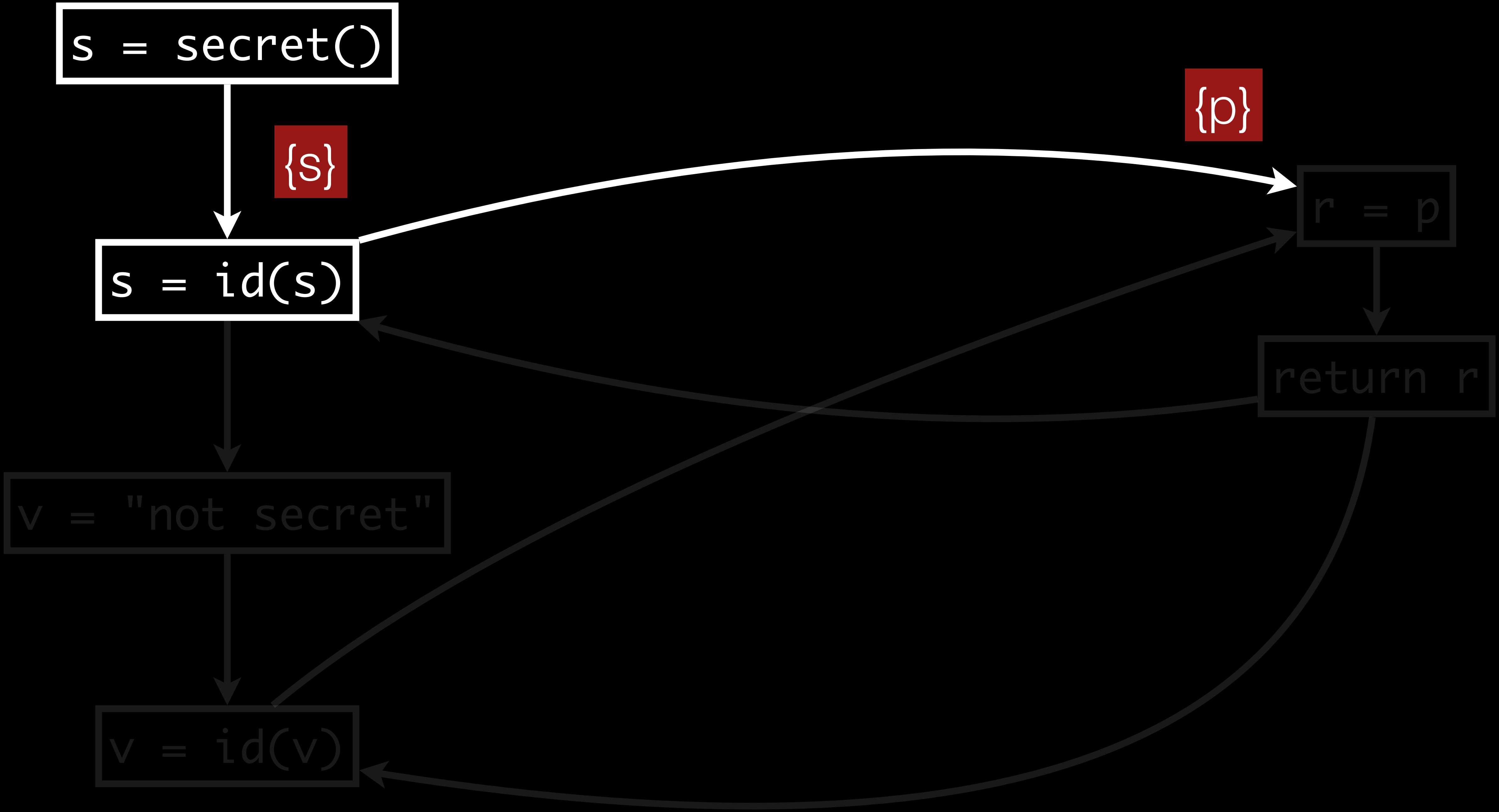

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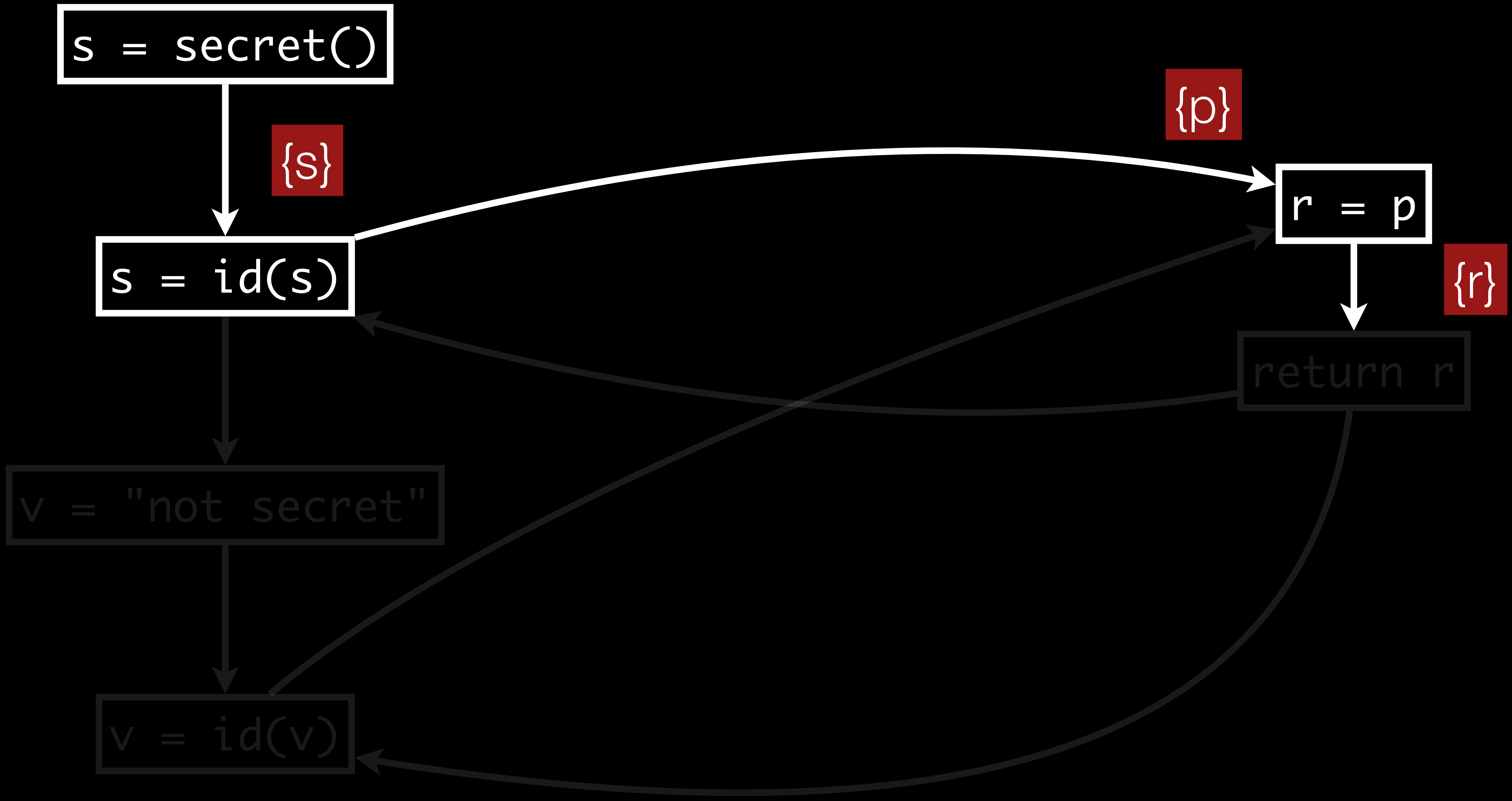

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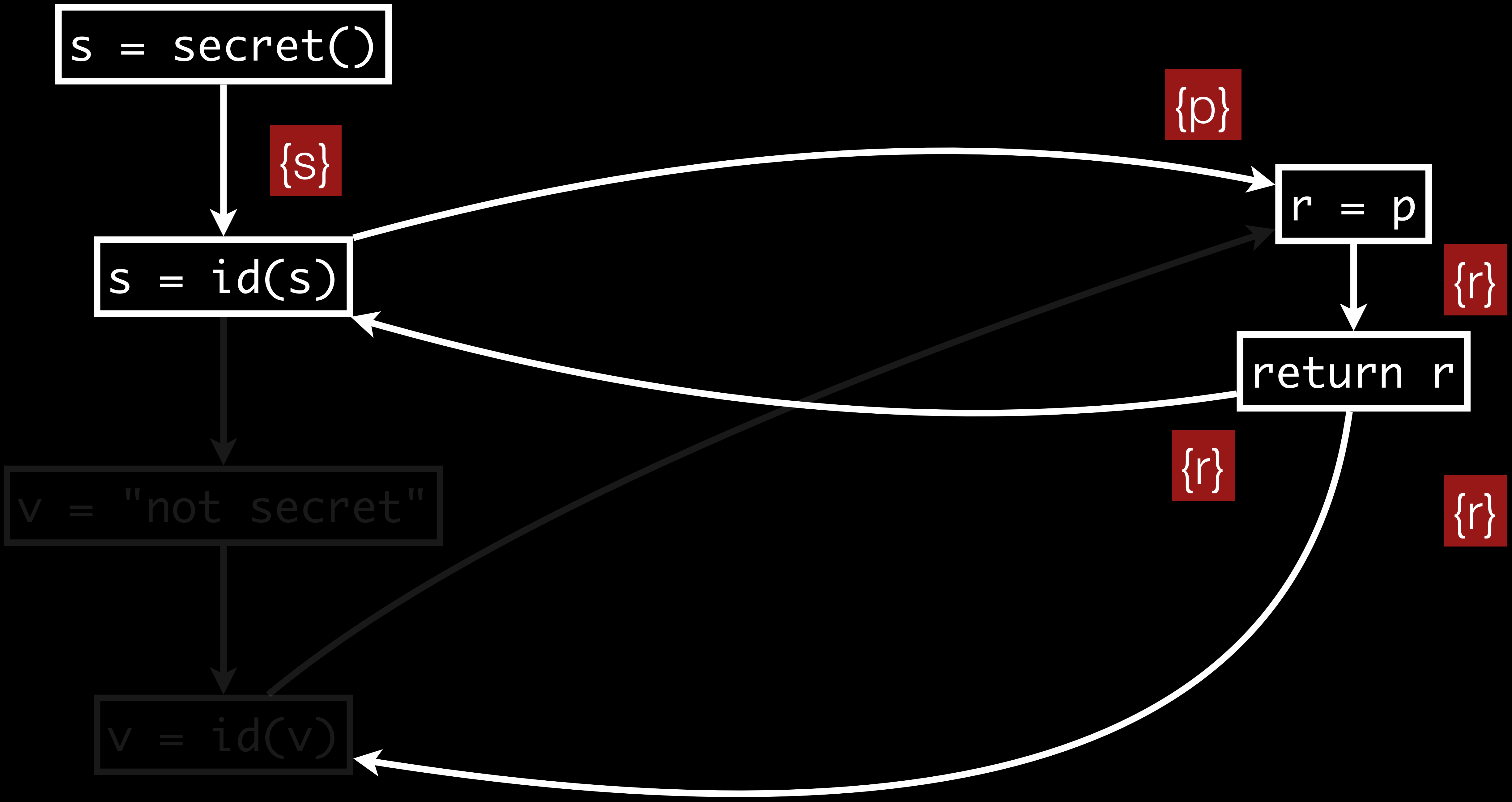

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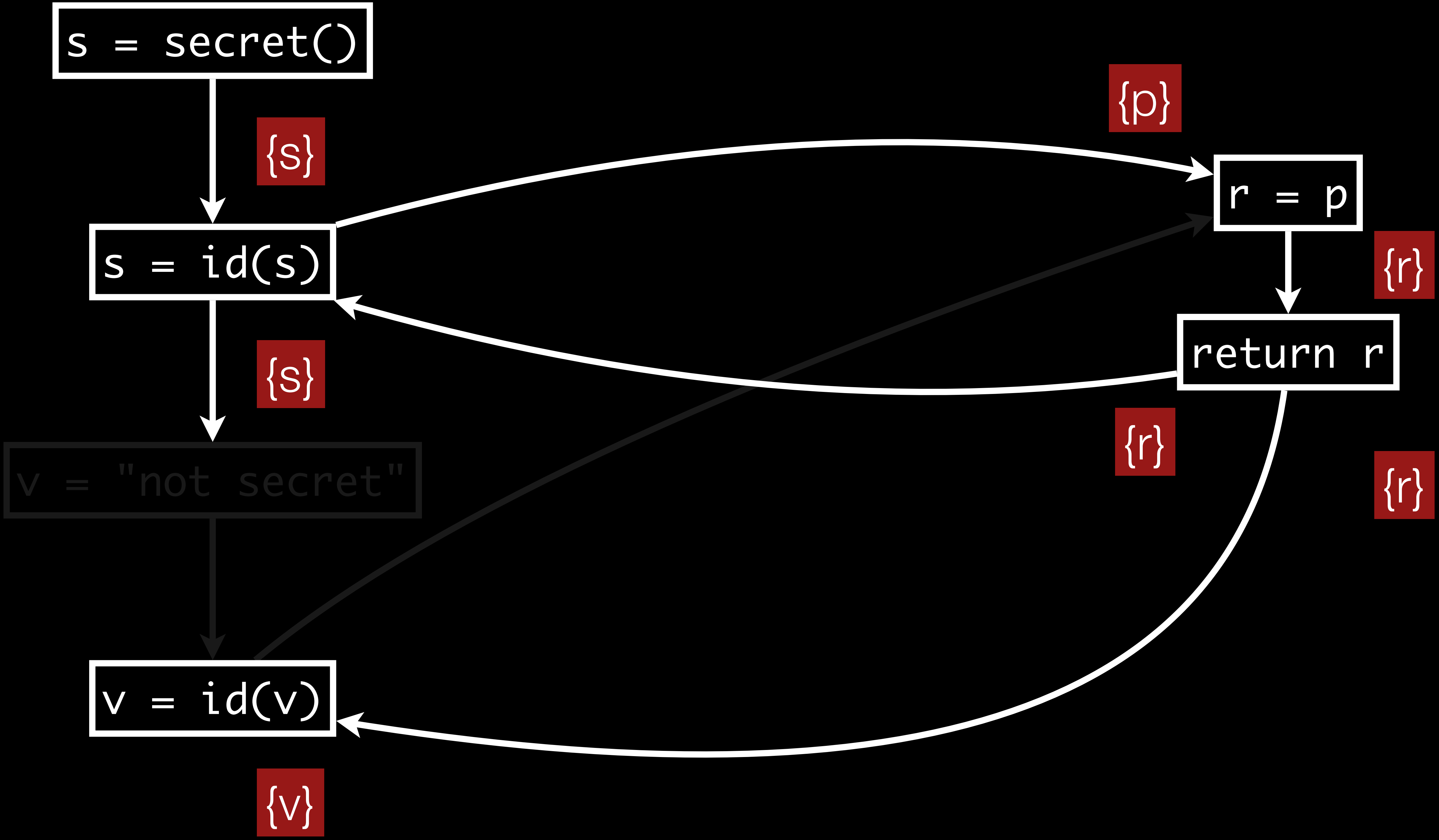

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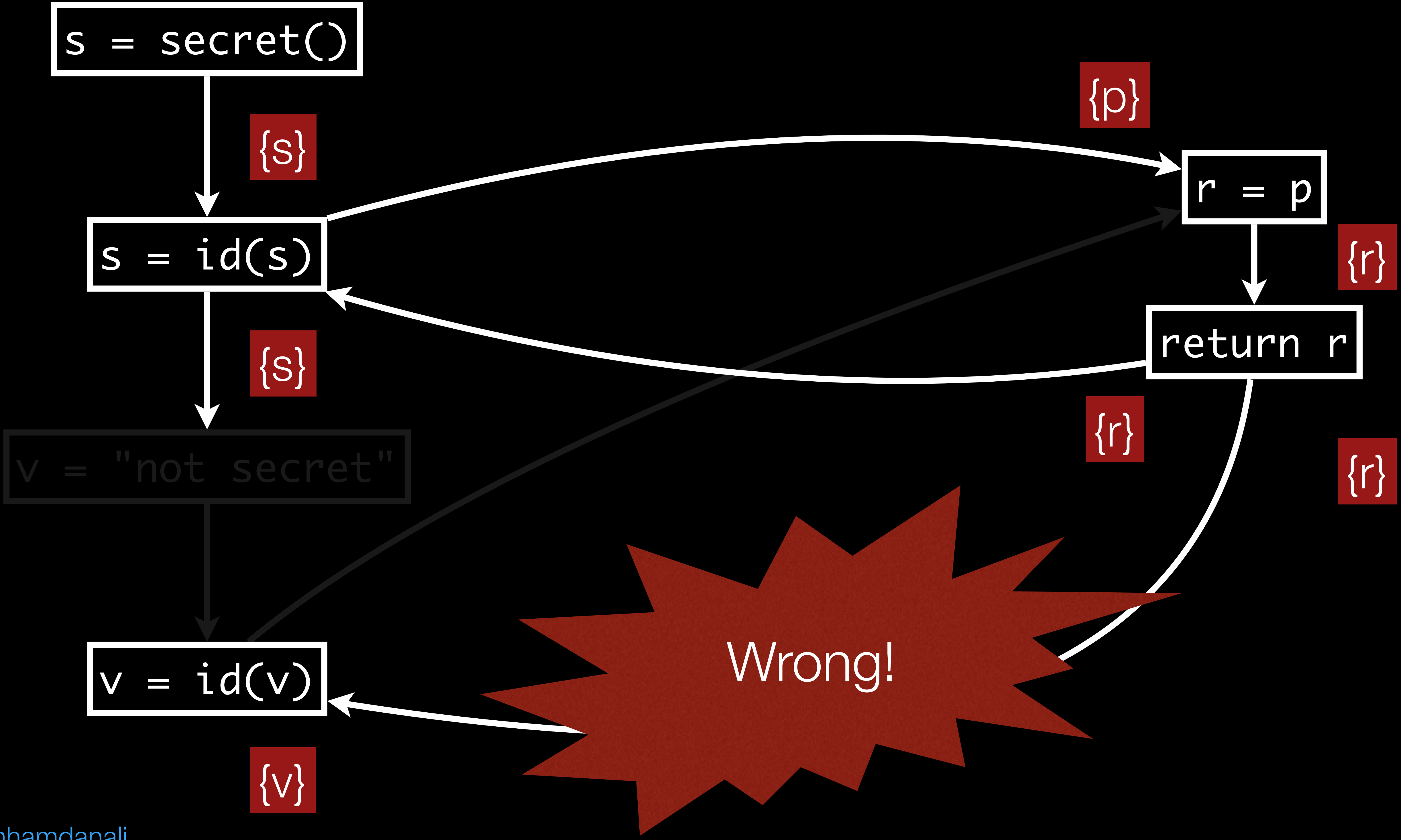

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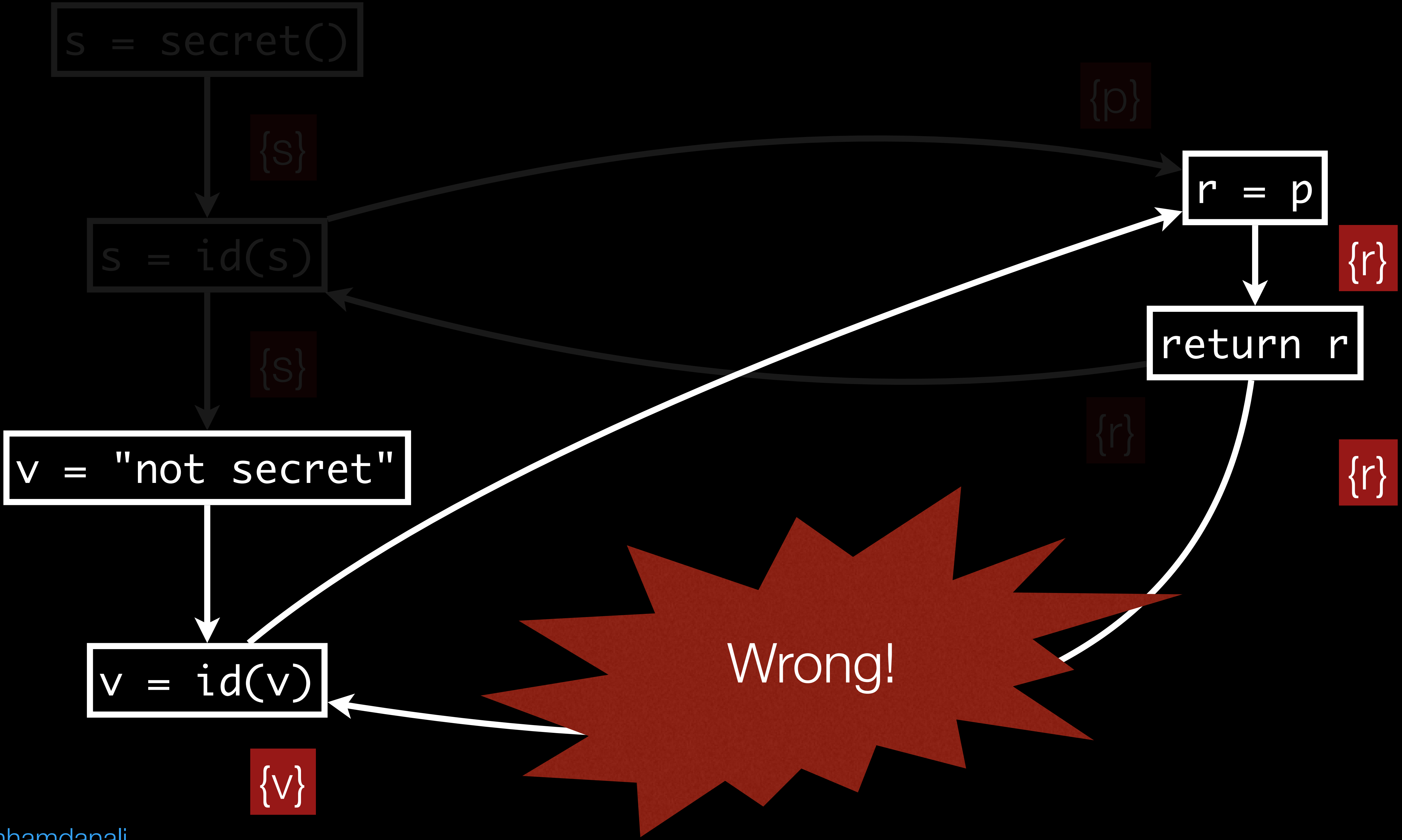

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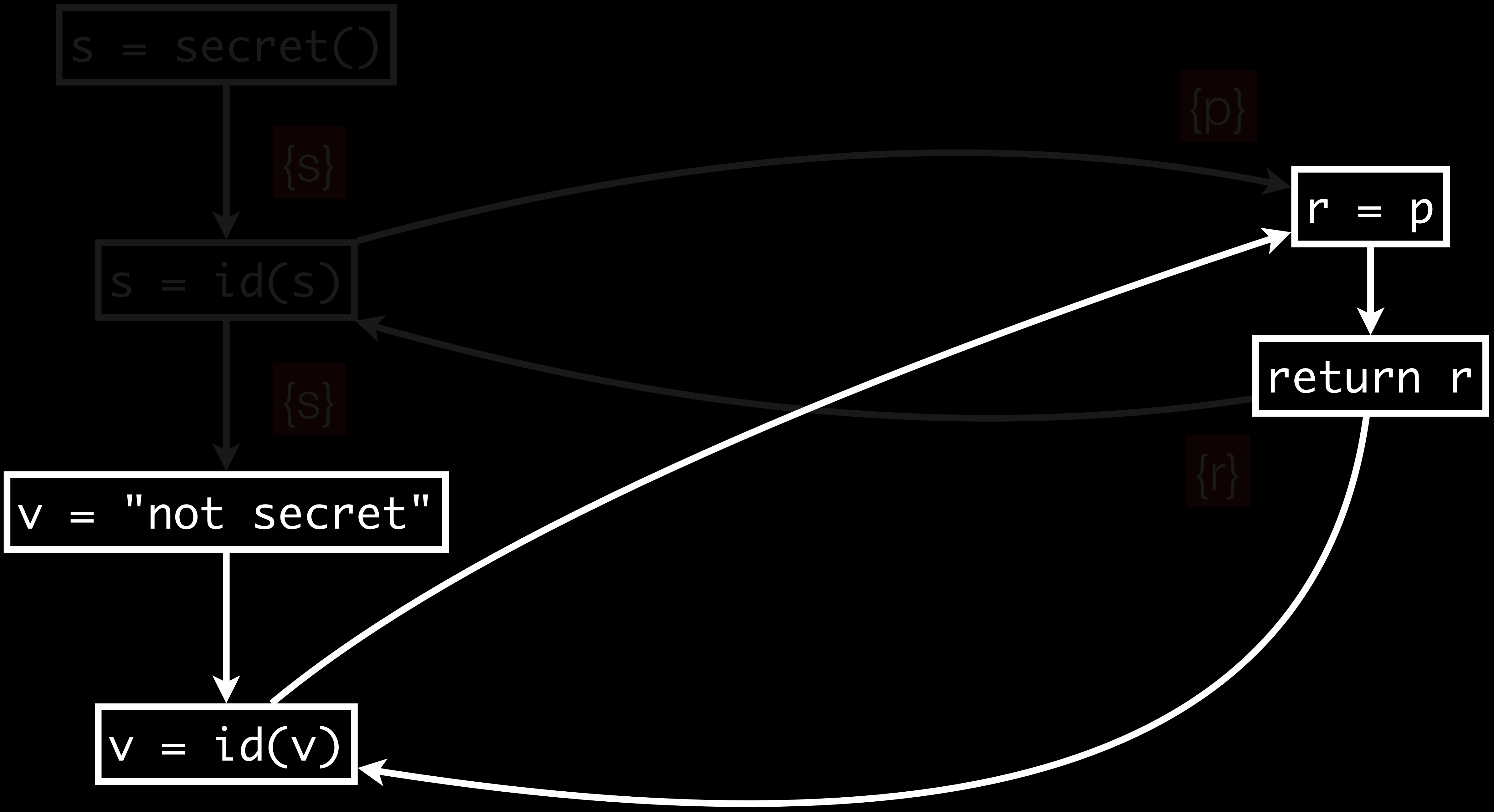

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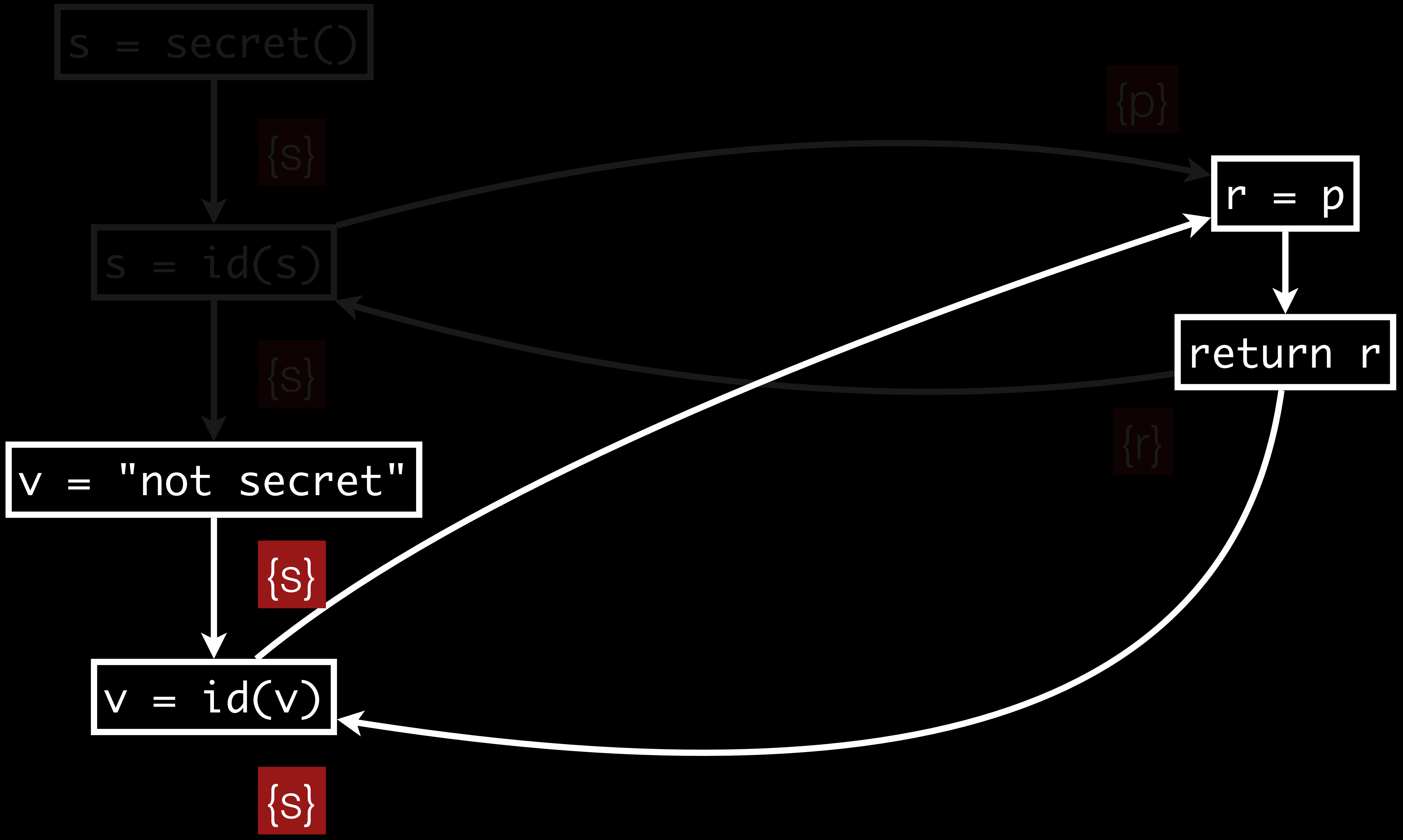

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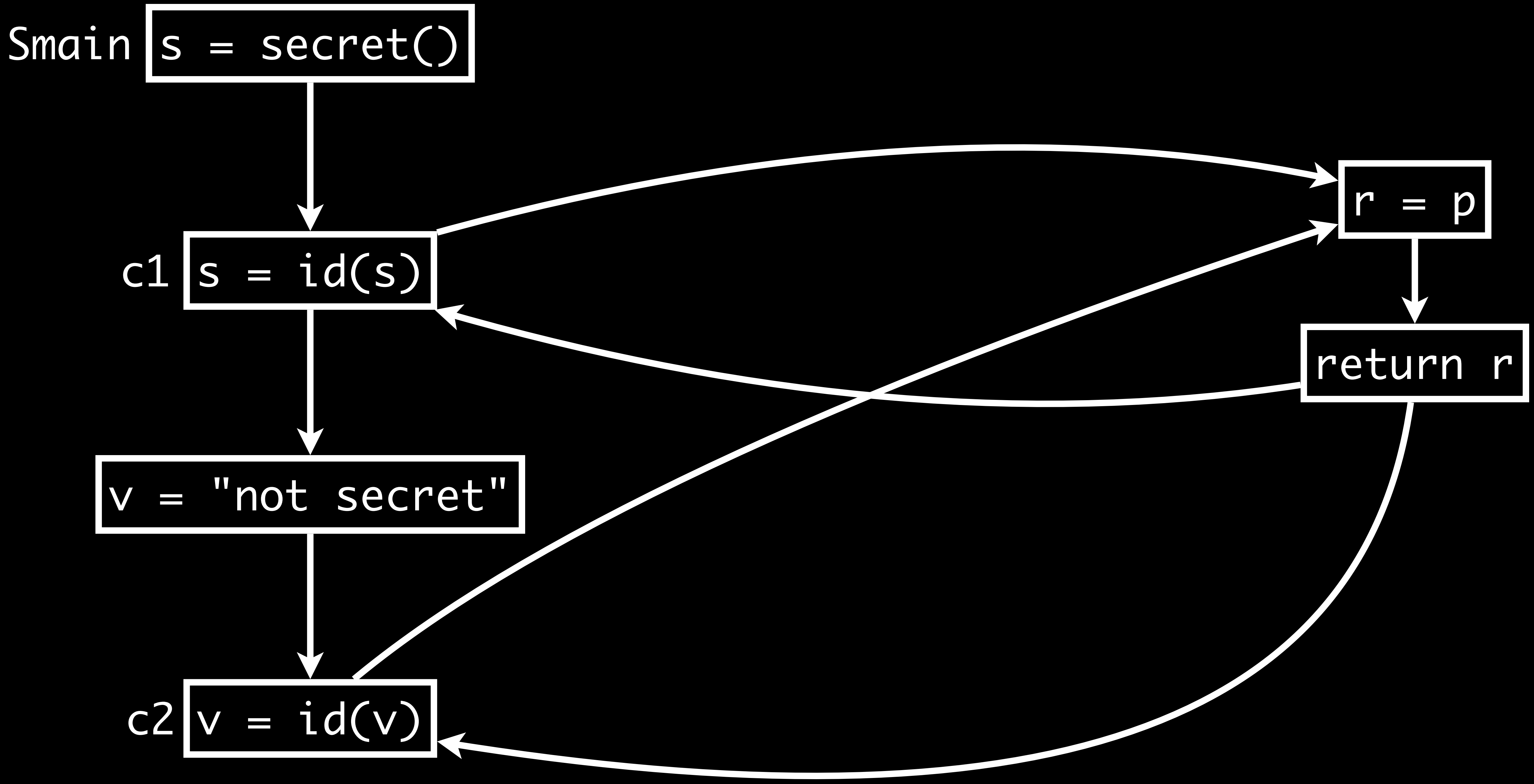

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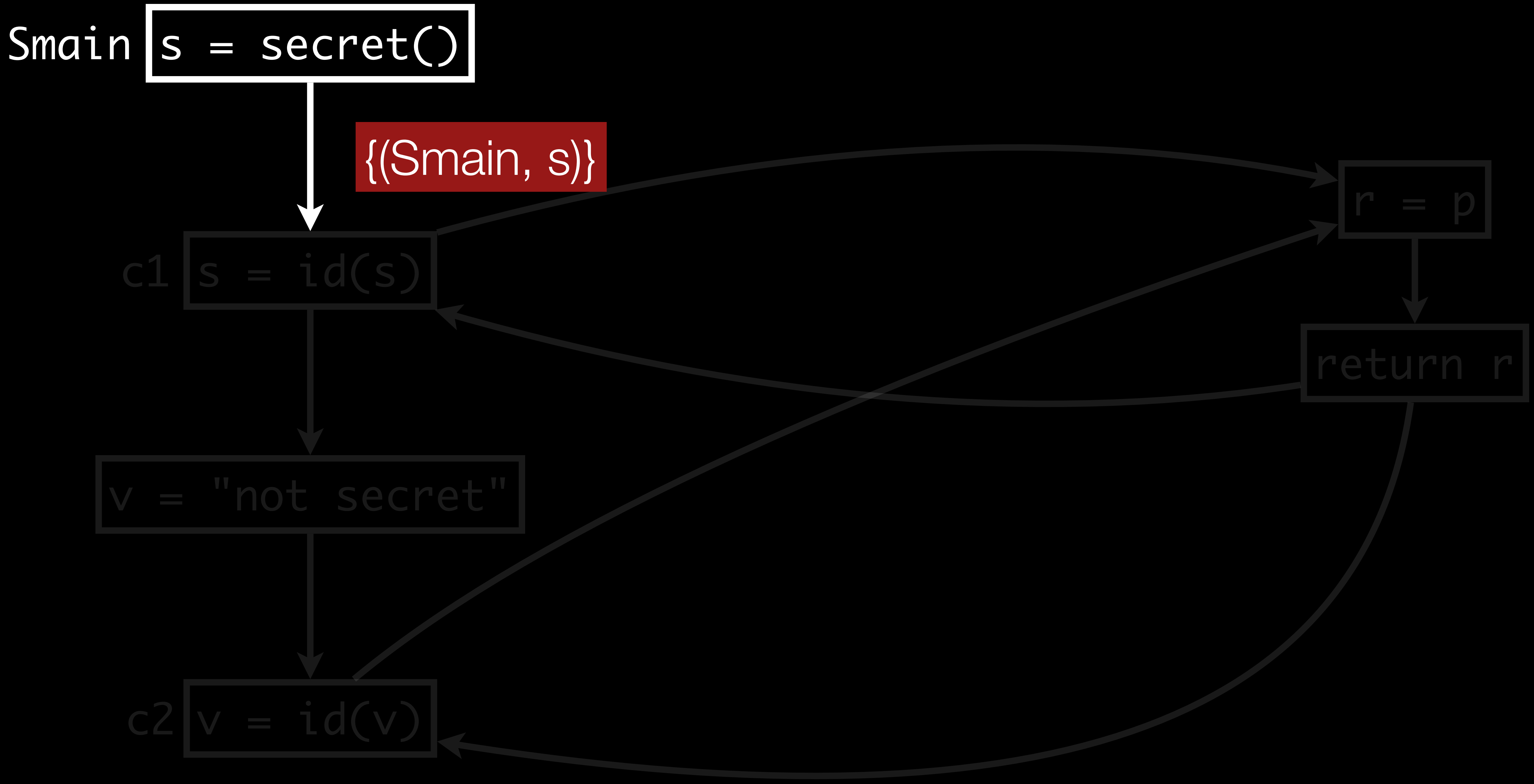

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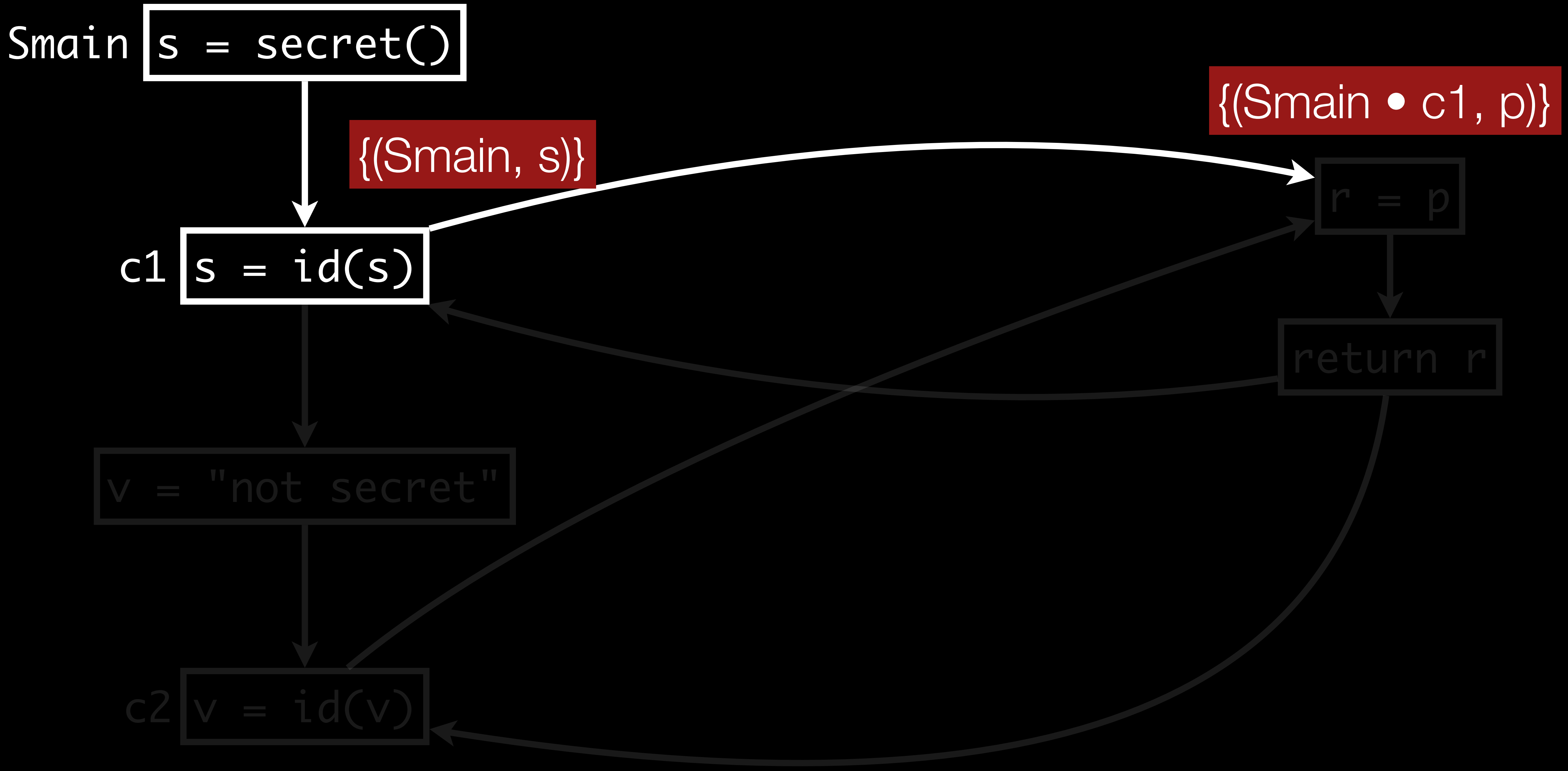

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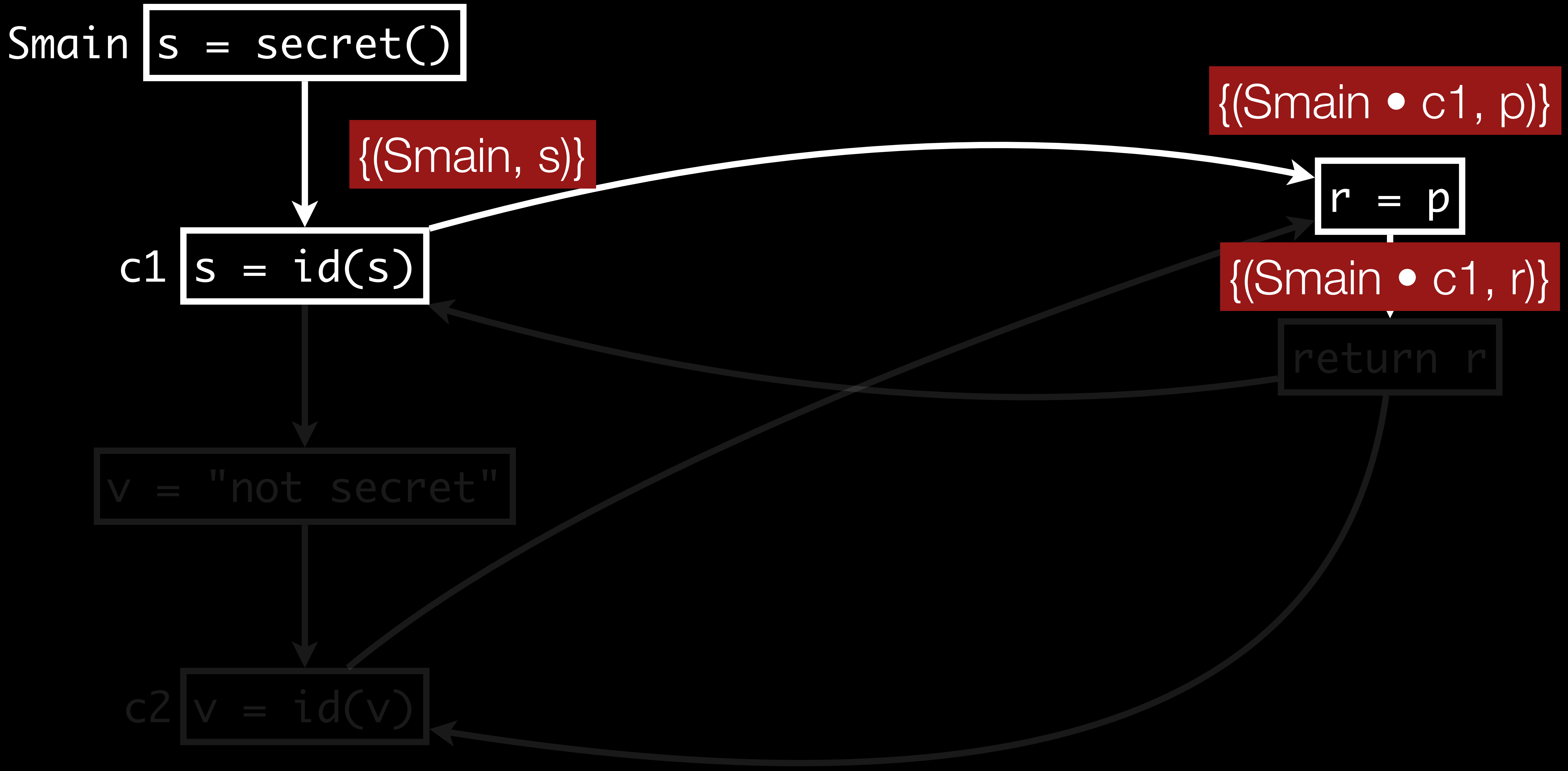

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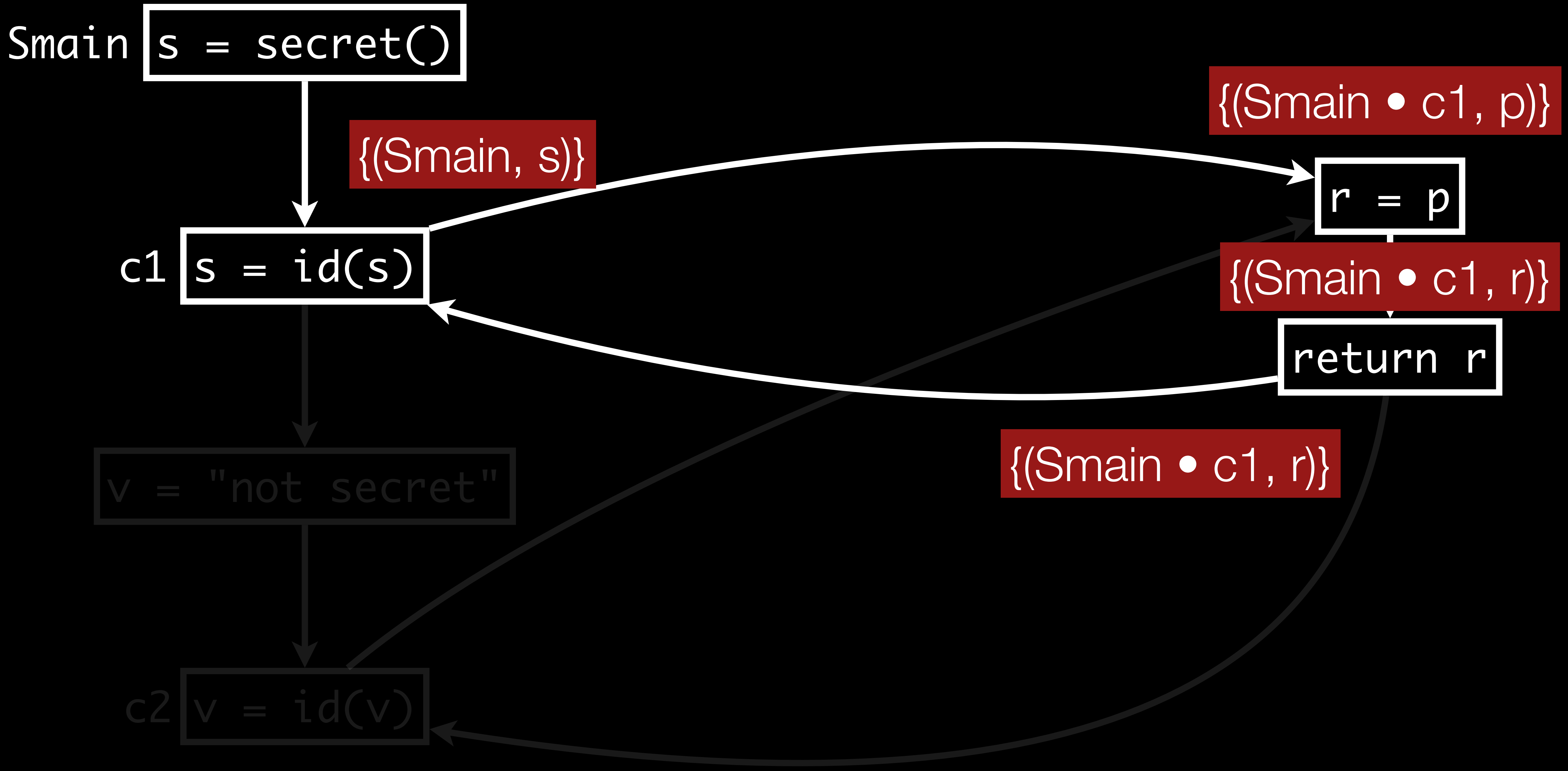

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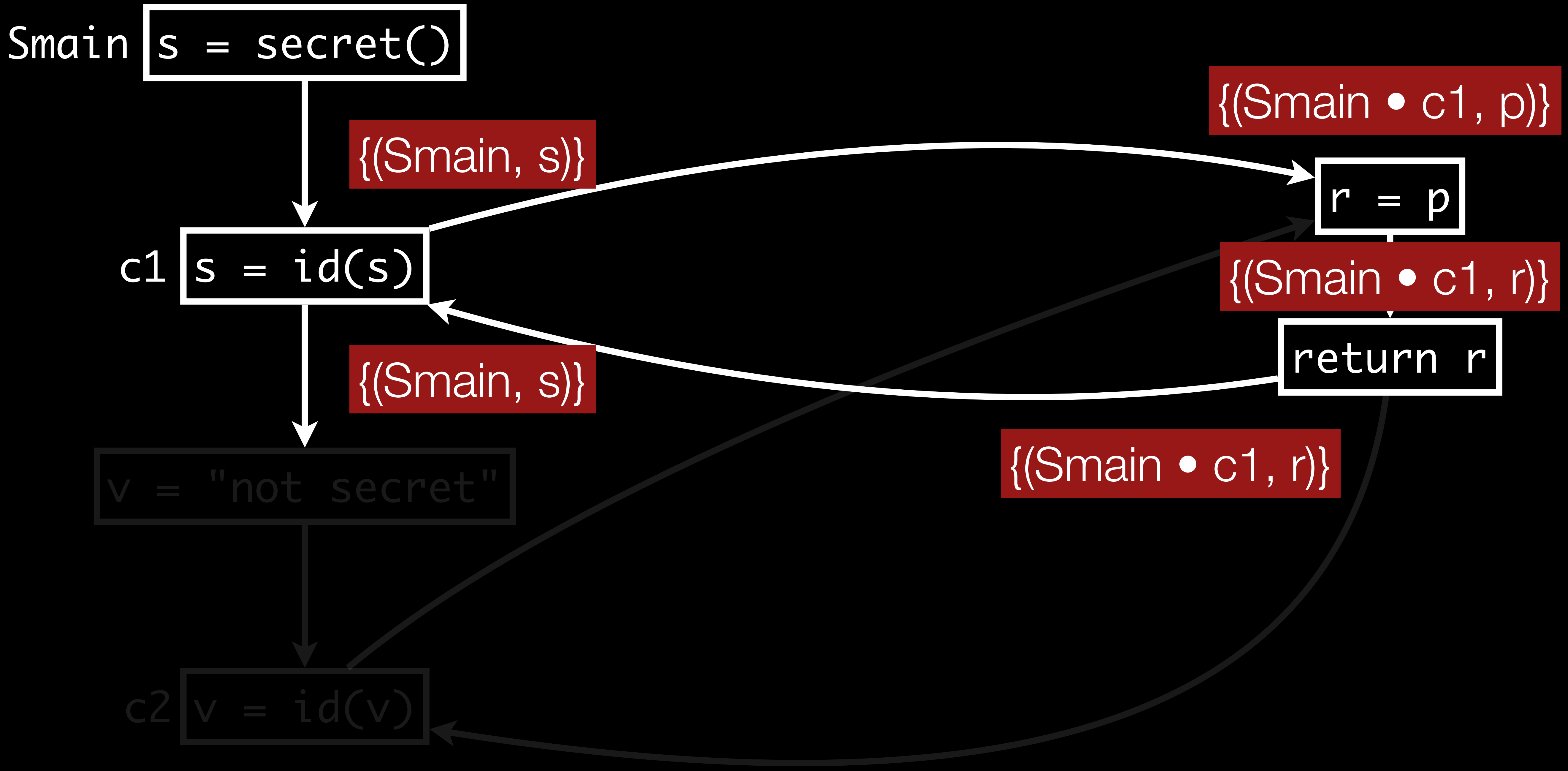

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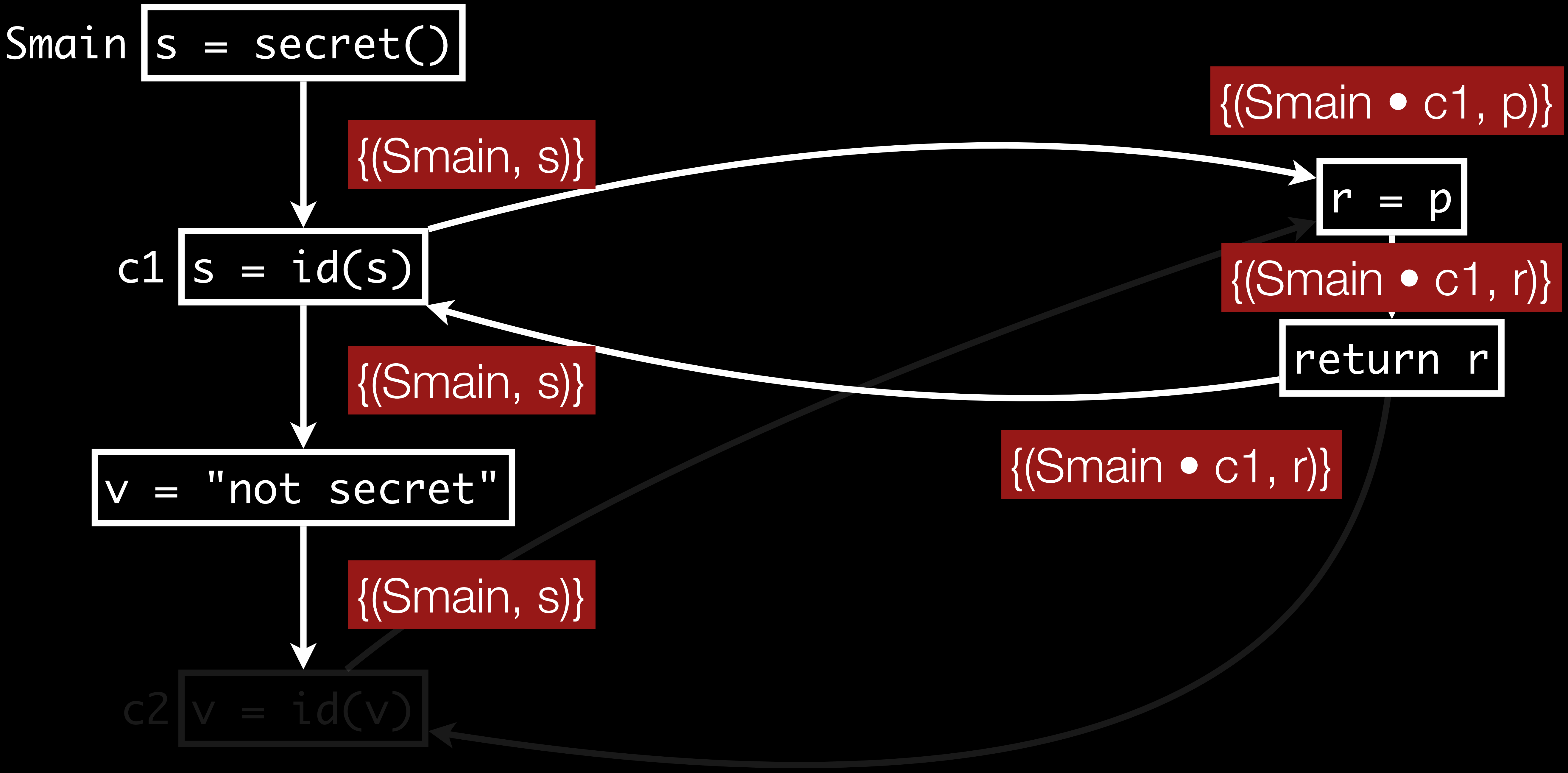
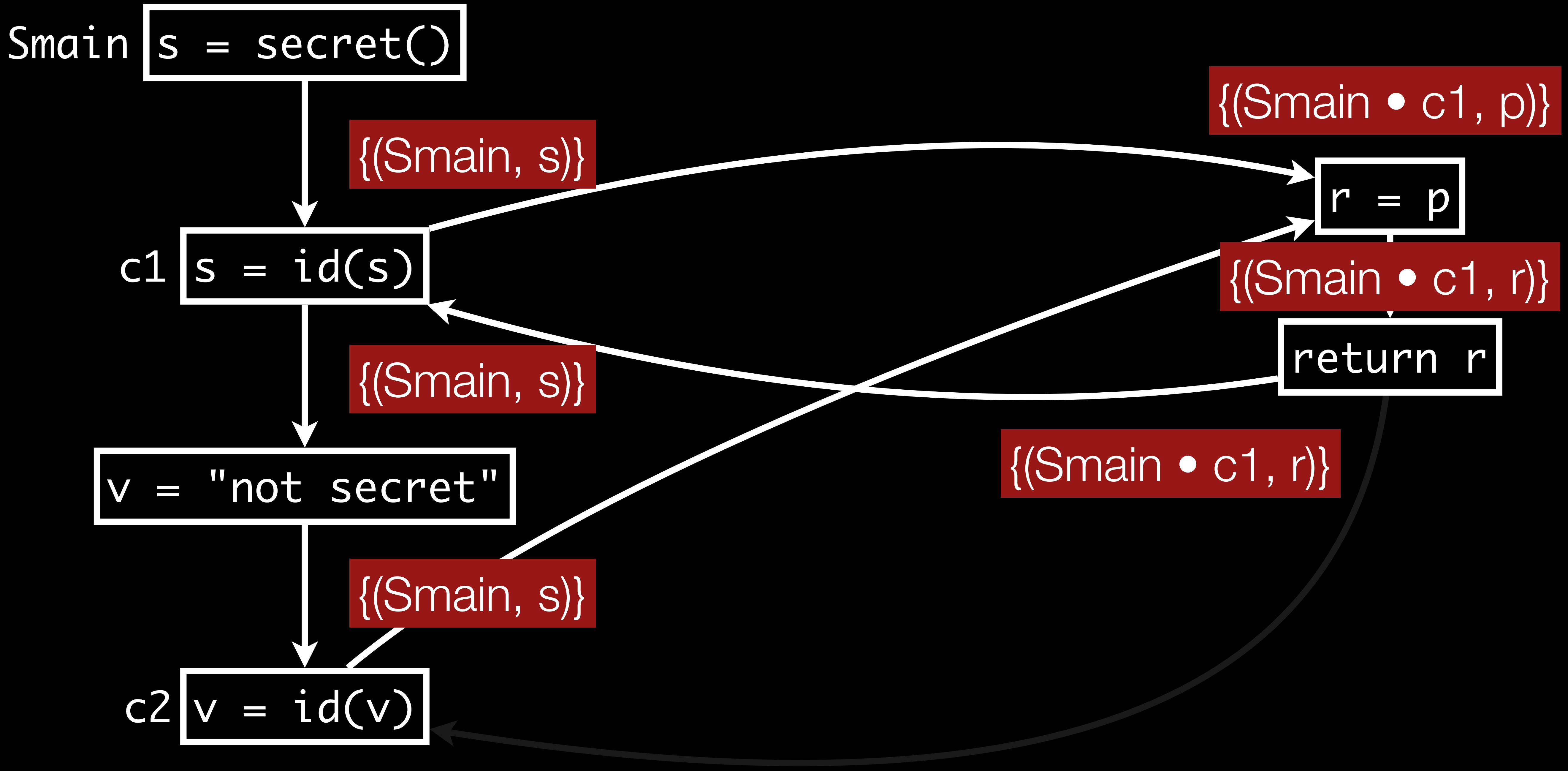


# Call Strings



Smain `s = secret()`

{(Smain, s)}

c1 `s = id(s)`

{(Smain, s)}

`v = "not secret"`

{(Smain, s)}

c2 `v = id(v)`

{(Smain • c1, p)}

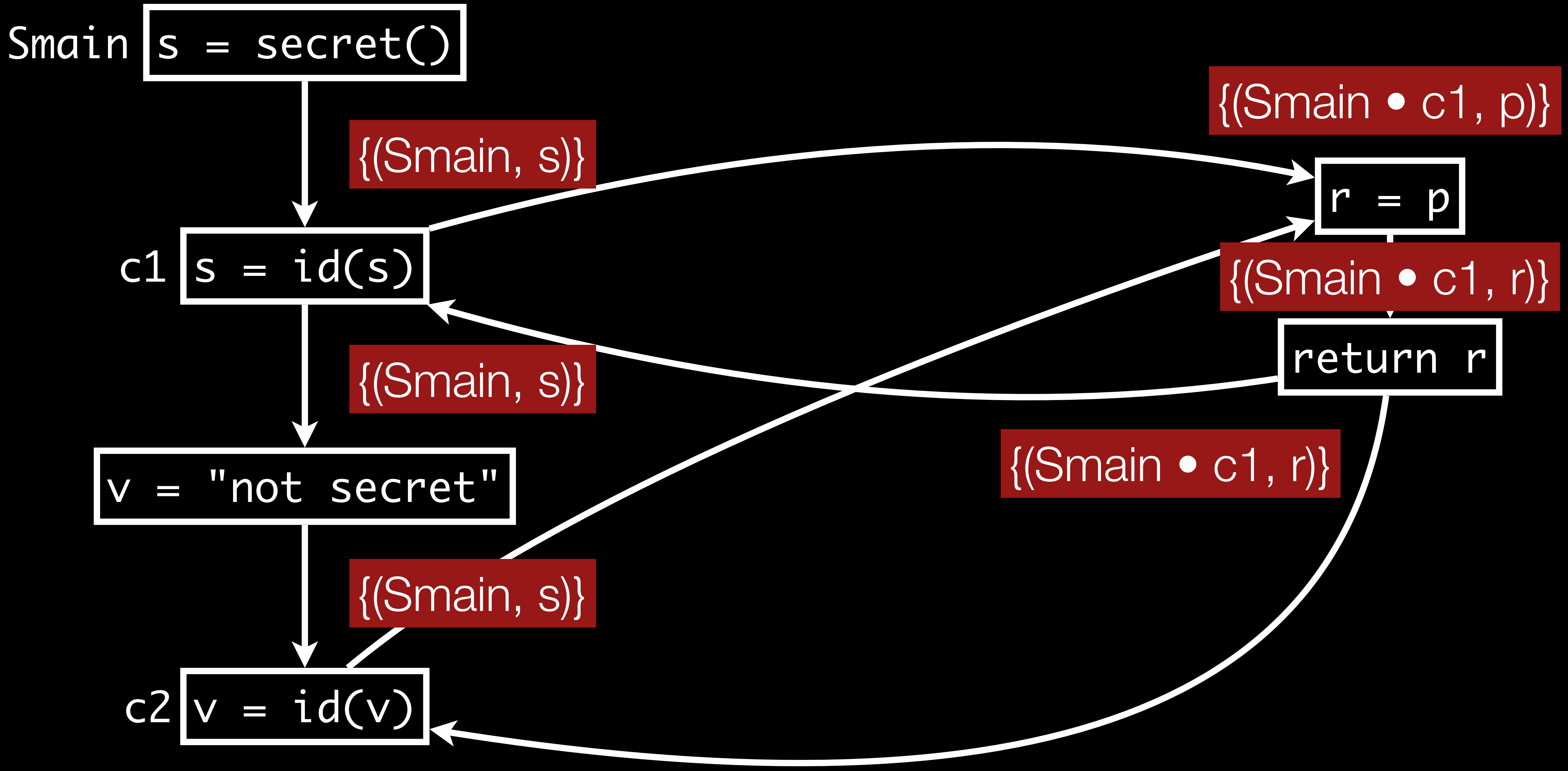
`r = p`

{(Smain • c1, r)}

`return r`

{(Smain • c1, r)}

# Call Strings



Smain

```
s = secret()
```

{(Smain, s)}

c1

```
s = id(s)
```

{(Smain, s)}

```
v = "not secret"
```

{(Smain, s)}

c2

```
v = id(v)
```

{(Smain • c1, p)}

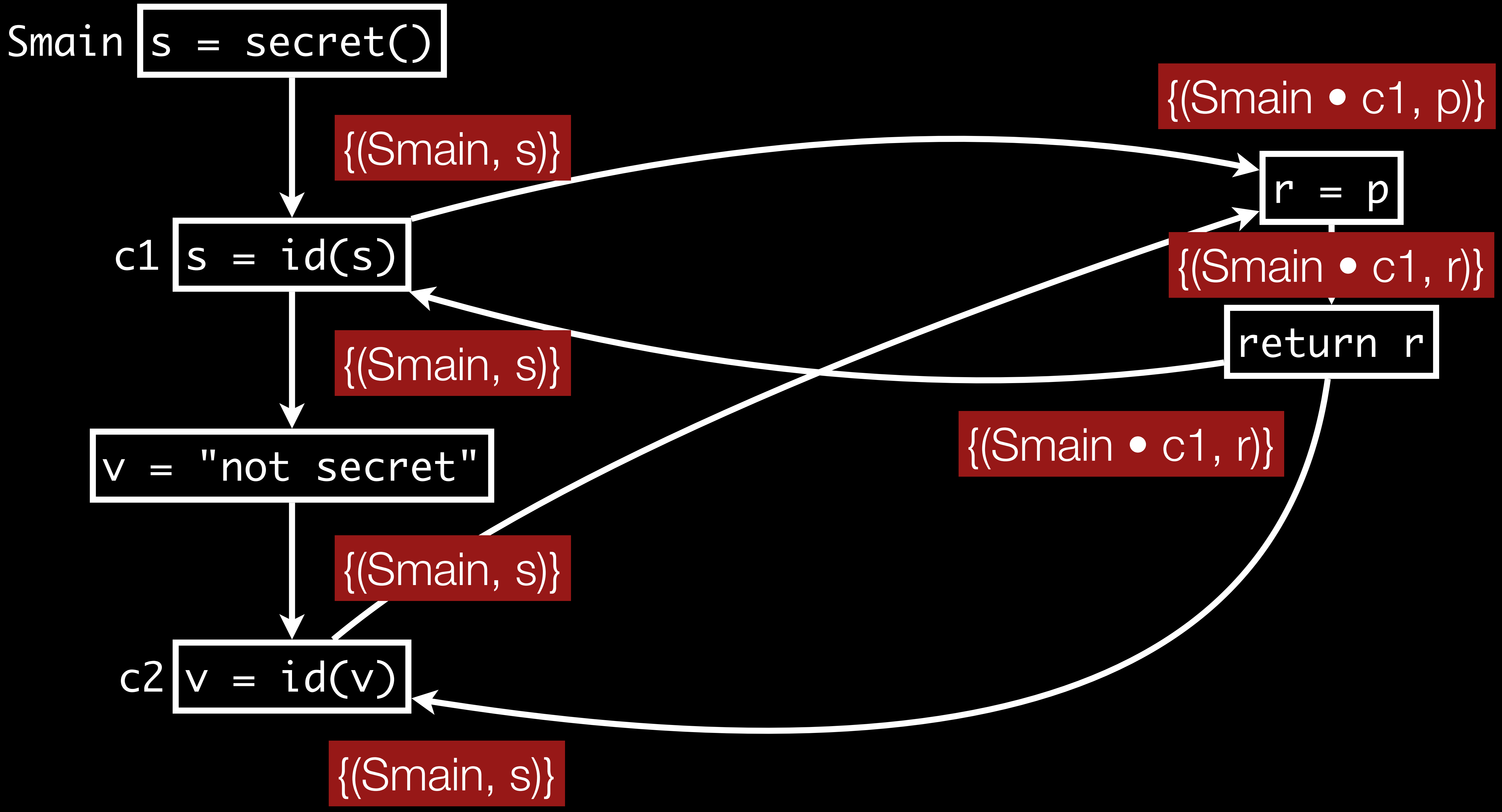
```
r = p
```

{(Smain • c1, r)}

```
return r
```

{(Smain • c1, r)}

# Call Strings



# Call Strings
# General Algorithm

- Call edges push call site to the stack of calling contexts of each propagated value
- Return edges return only to method on top of the stack of calling contexts
- Handle merge points

# Call Strings
# Merging Facts

$$
\begin{aligned}
X \uplus Y = \{ <\sigma, x \sqcup y> \quad &<\sigma, x> \in X, <\sigma, y> \in Y\} \cup \\
\{ <\sigma, x> \quad &<\sigma, x> \in X, \forall z \in L, <\sigma, z> \notin Y\} \cup \\
\{ <\sigma, y> \quad &<\sigma, y> \in Y, \forall z \in L, <\sigma, z> \notin X\}
\end{aligned}
$$

Not quite…

# Problem:
# context length!

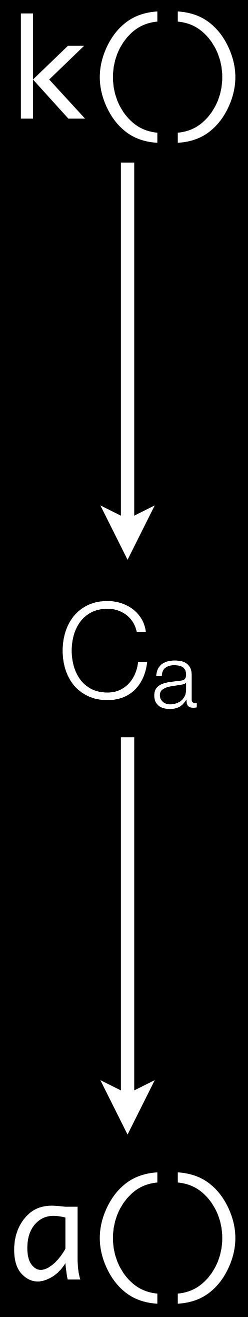
# Solution: k-limiting

Small k =>
imprecise

large k =>
poor performance

… but how does it work anyways?

# Call Strings
## k-limiting



$(C_0 \bullet C_1 \bullet \ldots \bullet C_k)$

maintain suffix of length k

$(C_1 \bullet \ldots \bullet C_k \bullet C_a)$

# Call Strings
## k-limiting

- K = length of longest non-recursive call sequence
- |L| = lattice height
- # contexts = $K * (|L| + 1)^2$
- Khedker and Karkare [CC ’08] improved this bound to $K * (|L| + 1)$

# Call Strings
Recap

- Cloning vs inlining
- Context as string
- Merging call strings
- Context length
- K-limiting

# Functional Approach

# Functional Approach

… but why bother?

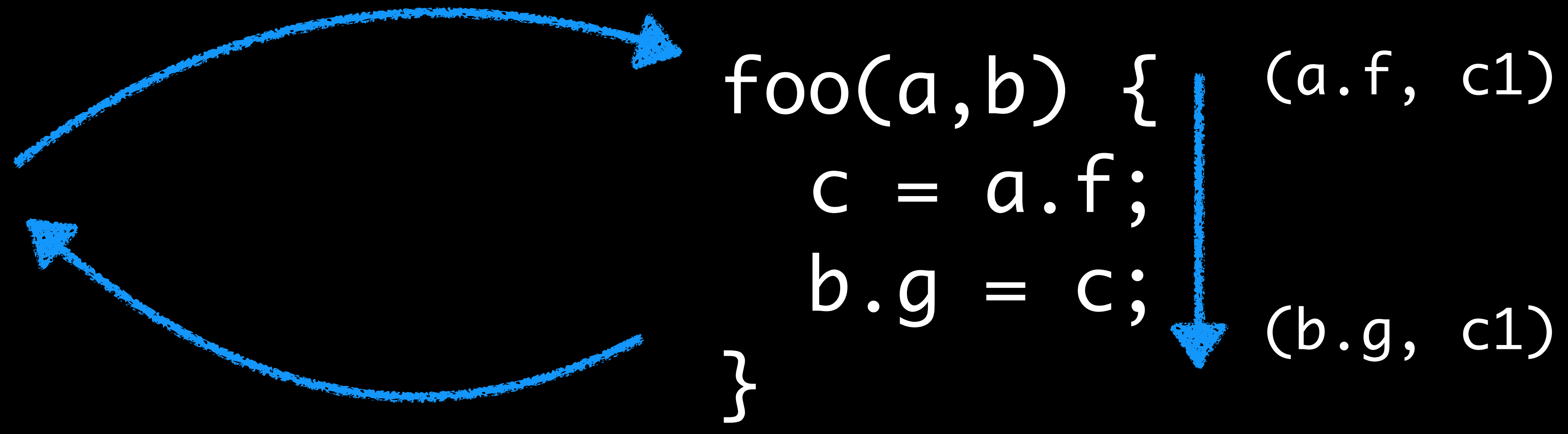
# Functional Approach

```
   h.f = myPassword();
   i.f = myPhoneNo();
   j.f = myCreditCardNo();

c1 foo(h,x);
c2 foo(i,y);
c3 foo(j,z);

   print(x.g);
   print(y.g);
   print(z.g);
```

```
foo(a,b) {
  c = a.f;
  b.g = c;
}
```

# Functional Approach

```
   h.f = myPassword();
   i.f = myPhoneNo();
   j.f = myCreditCardNo();
```



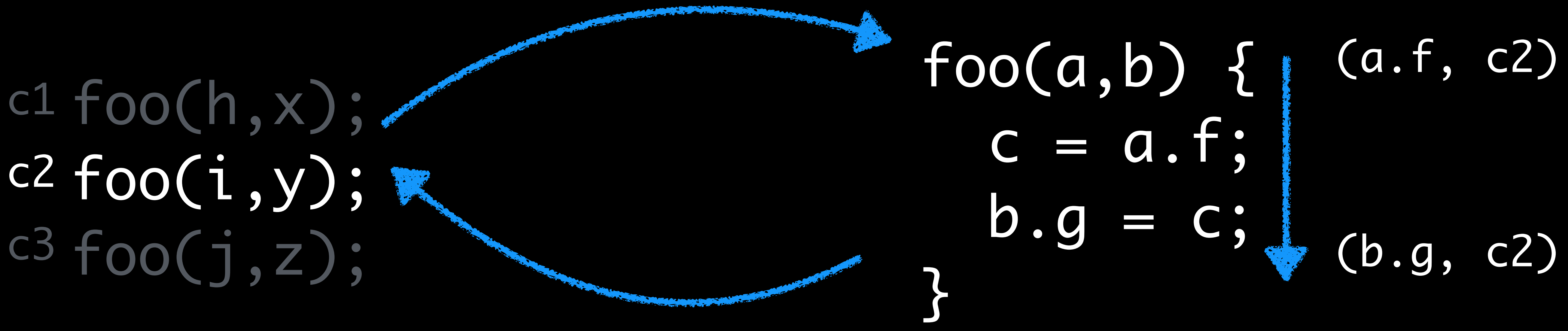
```
c1 foo(h,x);
c2 foo(i,y);
c3 foo(j,z);
```

```
foo(a,b) {      (a.f, c1)
  c = a.f;
  b.g = c;      (b.g, c1)
}
```

```
   print(x.g);
   print(y.g);
   print(z.g);
```

# Functional Approach

```
   h.f = myPassword();
   i.f = myPhoneNo();
   j.f = myCreditCardNo();
```



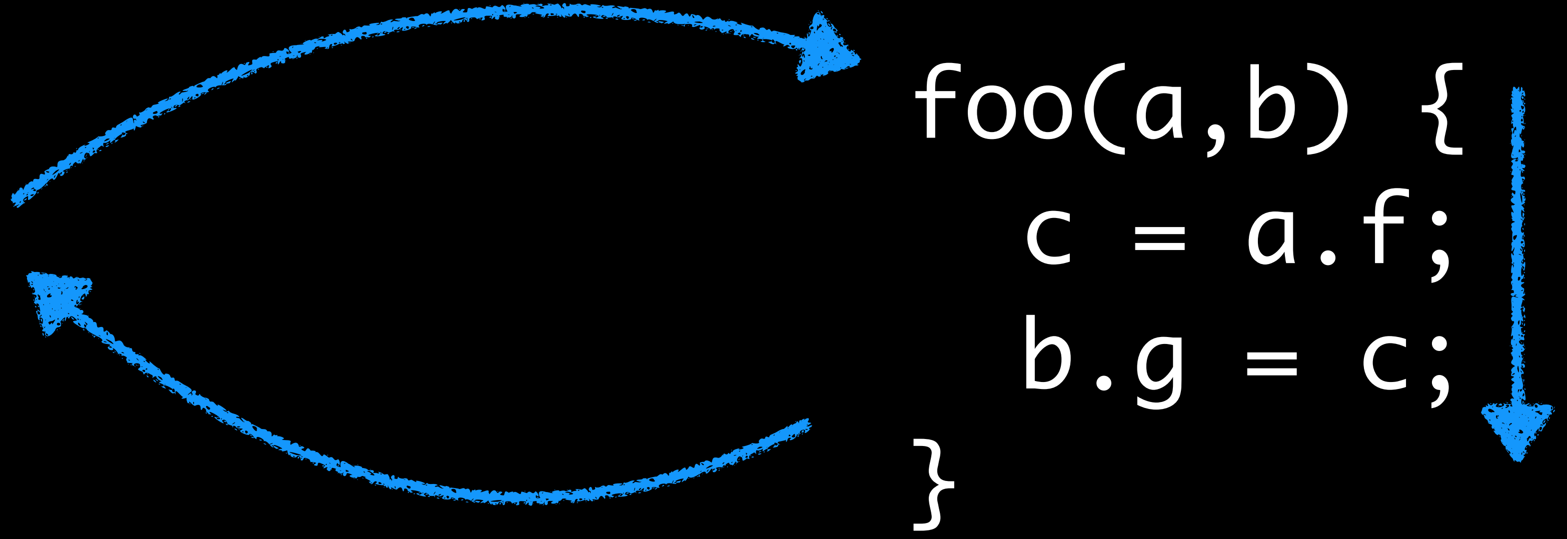
```
c1 foo(h,x);
c2 foo(i,y);
c3 foo(j,z);
```

```
foo(a,b) {
  c = a.f;
  b.g = c;
}
```

```
   print(x.g);
   print(y.g);
   print(z.g);
```

# Functional Approach

```
   h.f = myPassword();
   i.f = myPhoneNo();
   j.f = myCreditCardNo();

c1 foo(h,x);
c2 foo(i,y);
c3 foo(j,z);

   print(x.g);
   print(y.g);
   print(z.g);
```



```
foo(a,b) {
  c = a.f;
  b.g = c;
}
```

# Functional Approach

```
h.f = myPassword();
i.f = myPhoneNo();
j.f = my      rdNo();

c1

print(x.g);
print(y.g);
print(z.g);
```

Same method analyzed 3 times!!

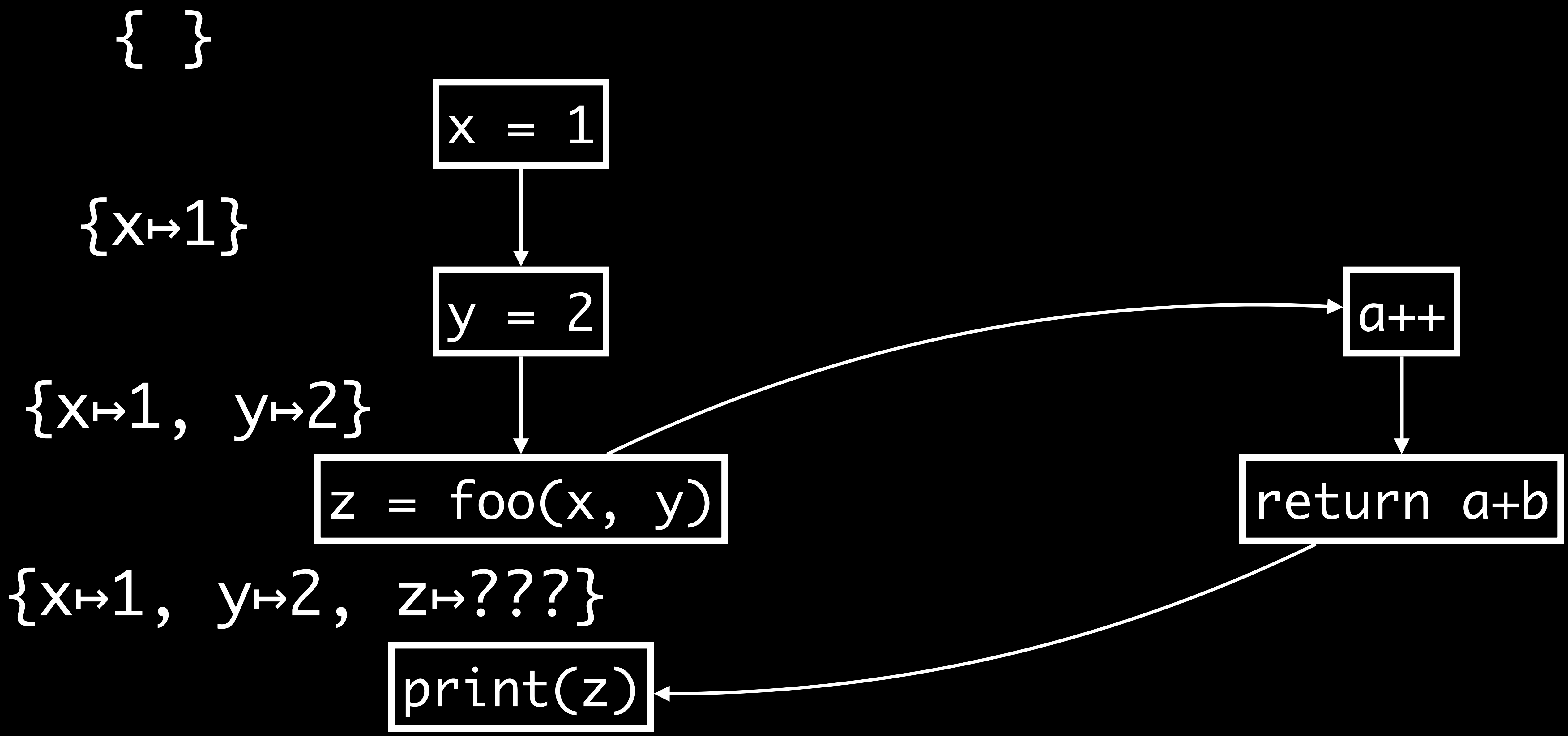
```
foo(a,b) {
   c = a.f;
   b.g = c;
}
```

```
(a.f, c1)
(a.f, c2)
(a.f, c3)

(b.g, c3)
(b.g, c2)
(b.g, c1)
```

# Functional Approach
# Example: Constant Propagation

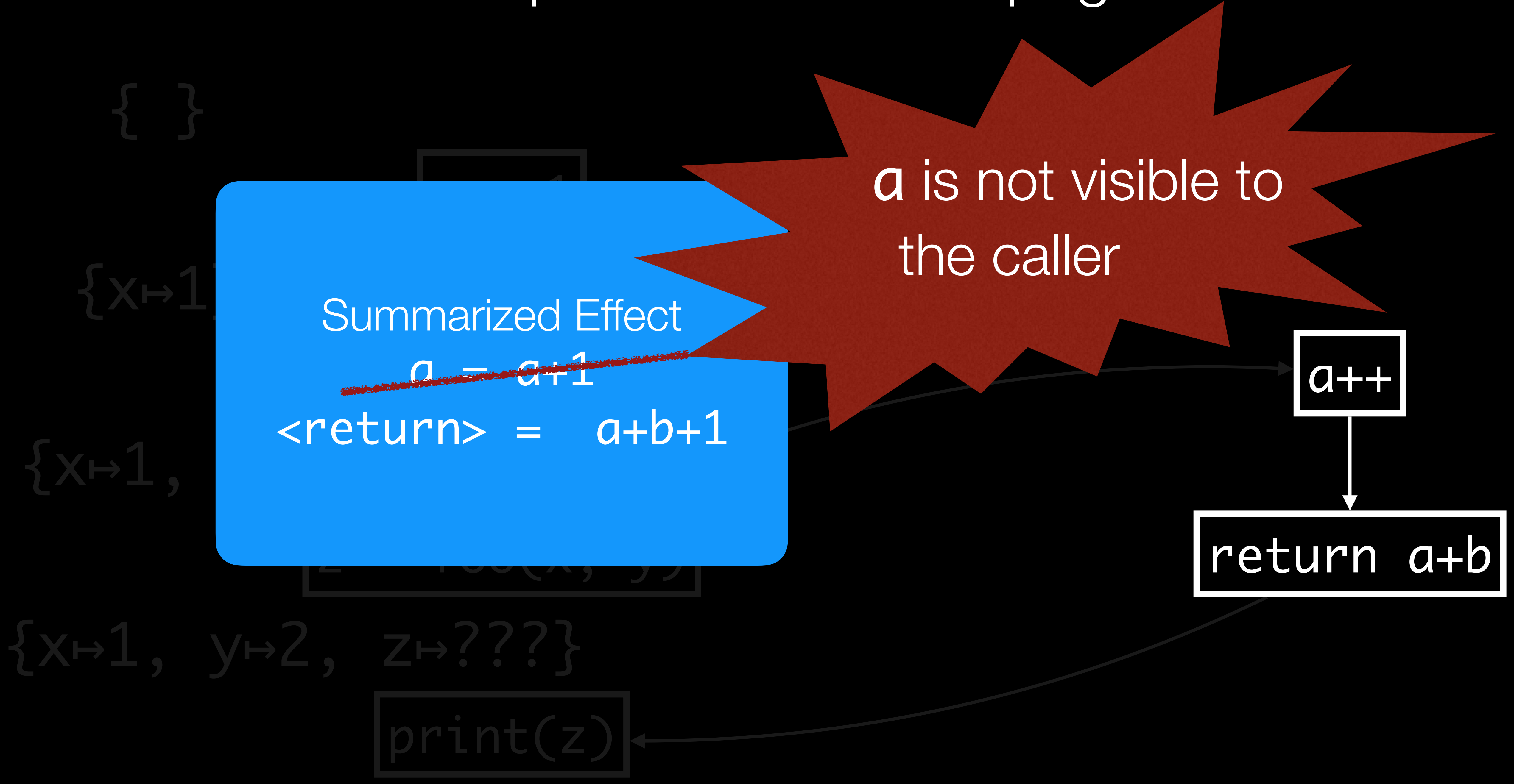
```
foo(a,b) {
  a++;
  return a+b;
}
```

# Functional Approach
# Example: Constant Propagation



```
{ }
x = 1
{x↦1}
y = 2
{x↦1, y↦2}
z = foo(x, y)
{x↦1, y↦2, z↦???}
print(z)
a++
return a+b
```

# Functional Approach
# Example: Constant Propagation



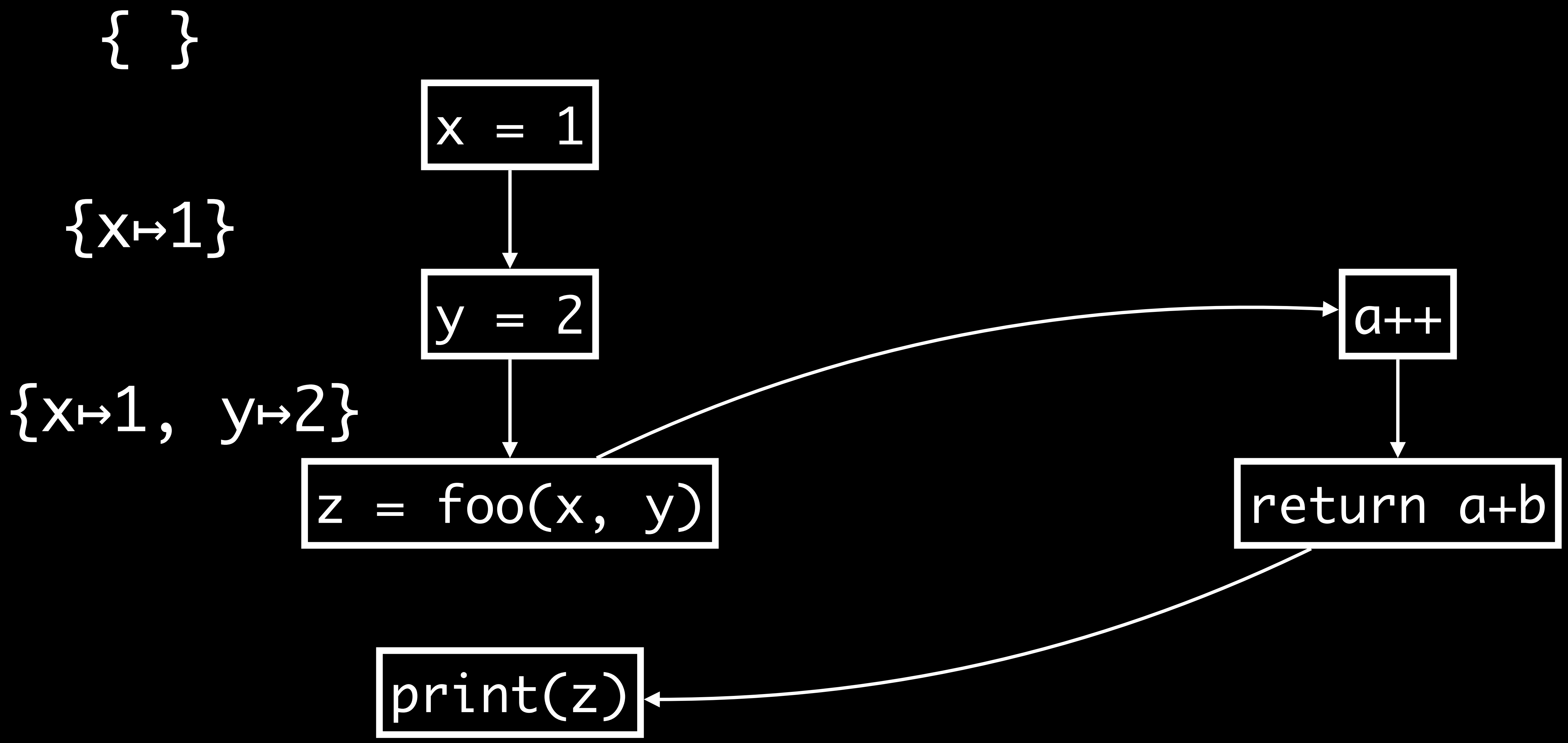
Summarized Effect

~~a = a+1~~

<return> = a+b+1

a is not visible to the caller

# Functional Approach
# Example: Constant Propagation



{ }

x = 1

{x↦1}

y = 2

{x↦1, y↦2}

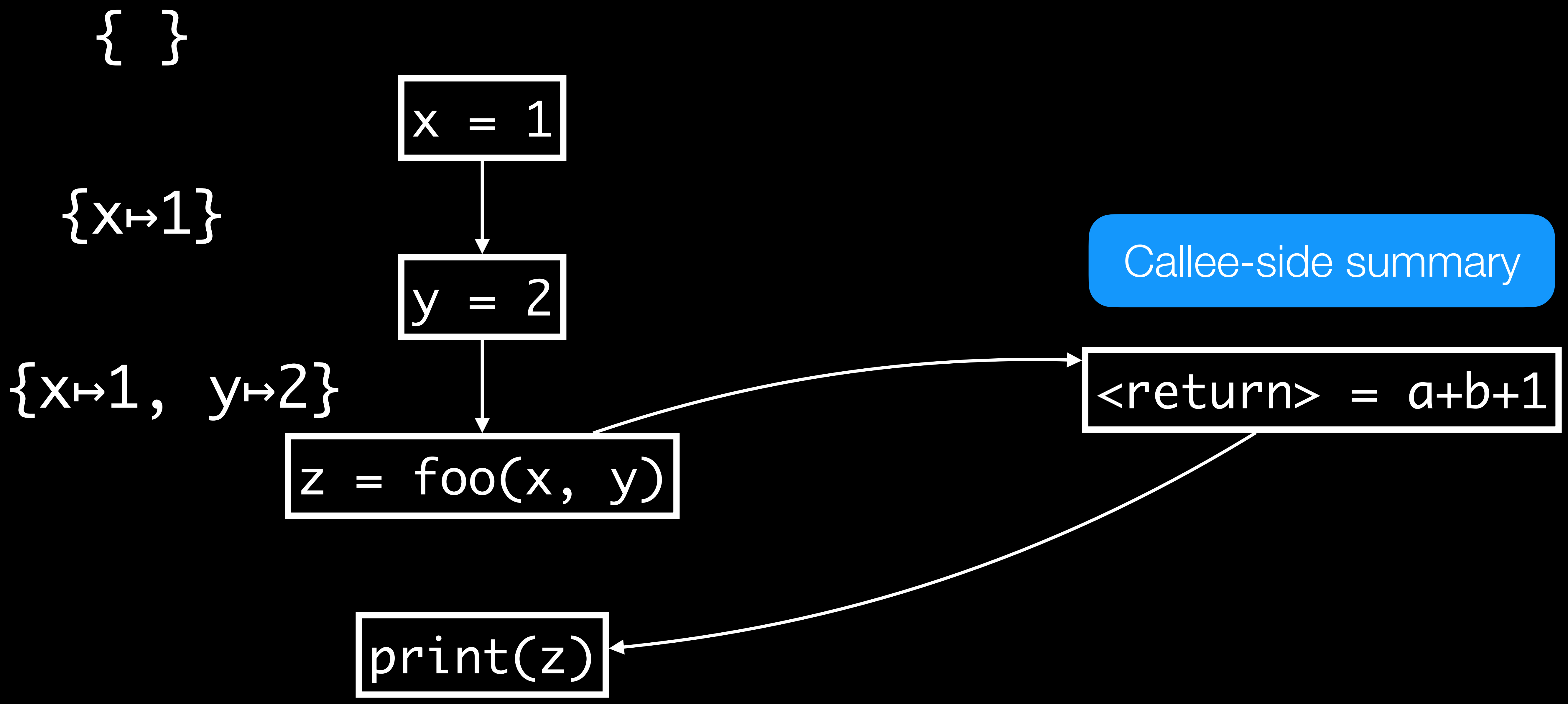
z = foo(x, y)

a++

return a+b

print(z)

# Functional Approach
# Example: Constant Propagation



{ }

x = 1

{x↦1}

y = 2

{x↦1, y↦2}

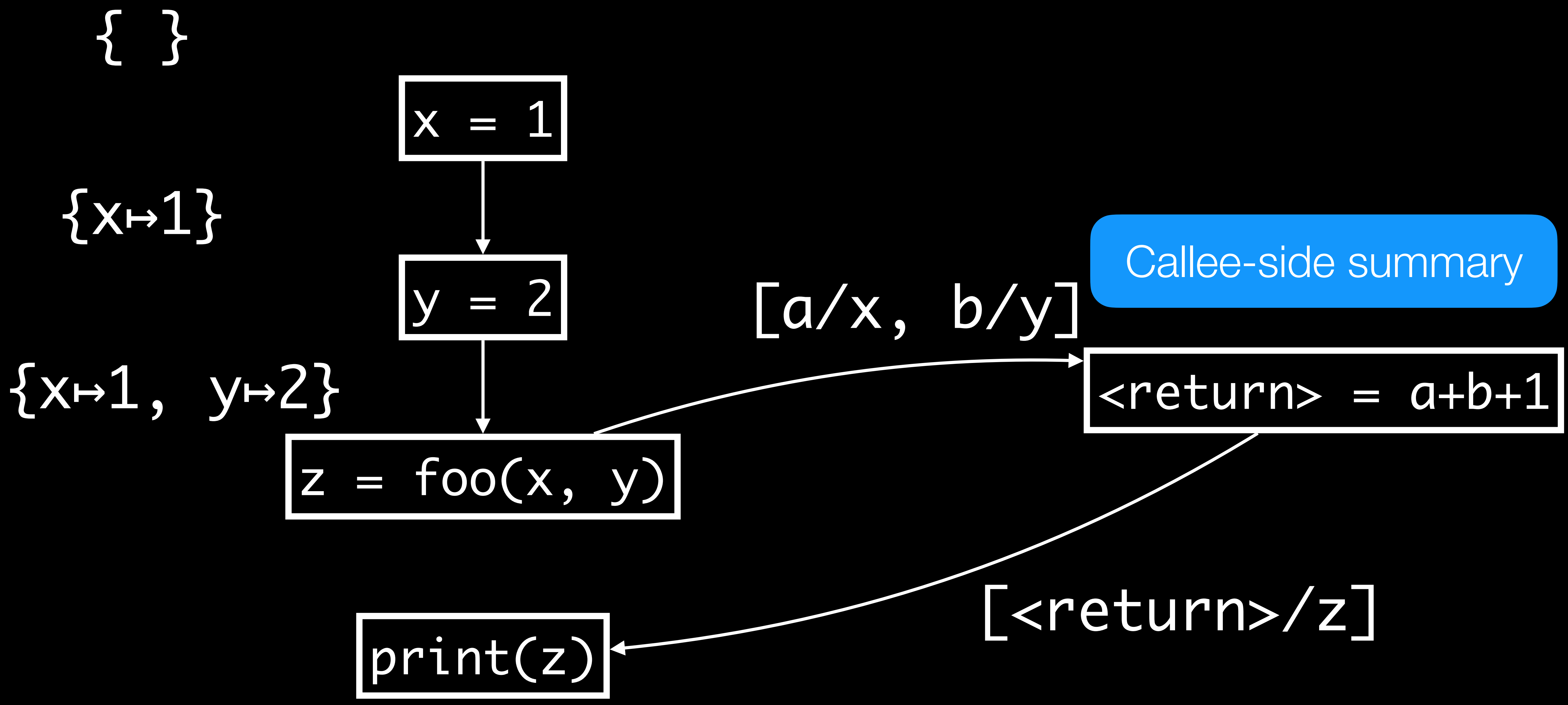
z = foo(x, y)

Callee-side summary

<return> = a+b+1

print(z)

# Functional Approach
# Example: Constant Propagation



{ }

x = 1

{x↦1}

y = 2

{x↦1, y↦2}

z = foo(x, y)

[a/x, b/y]

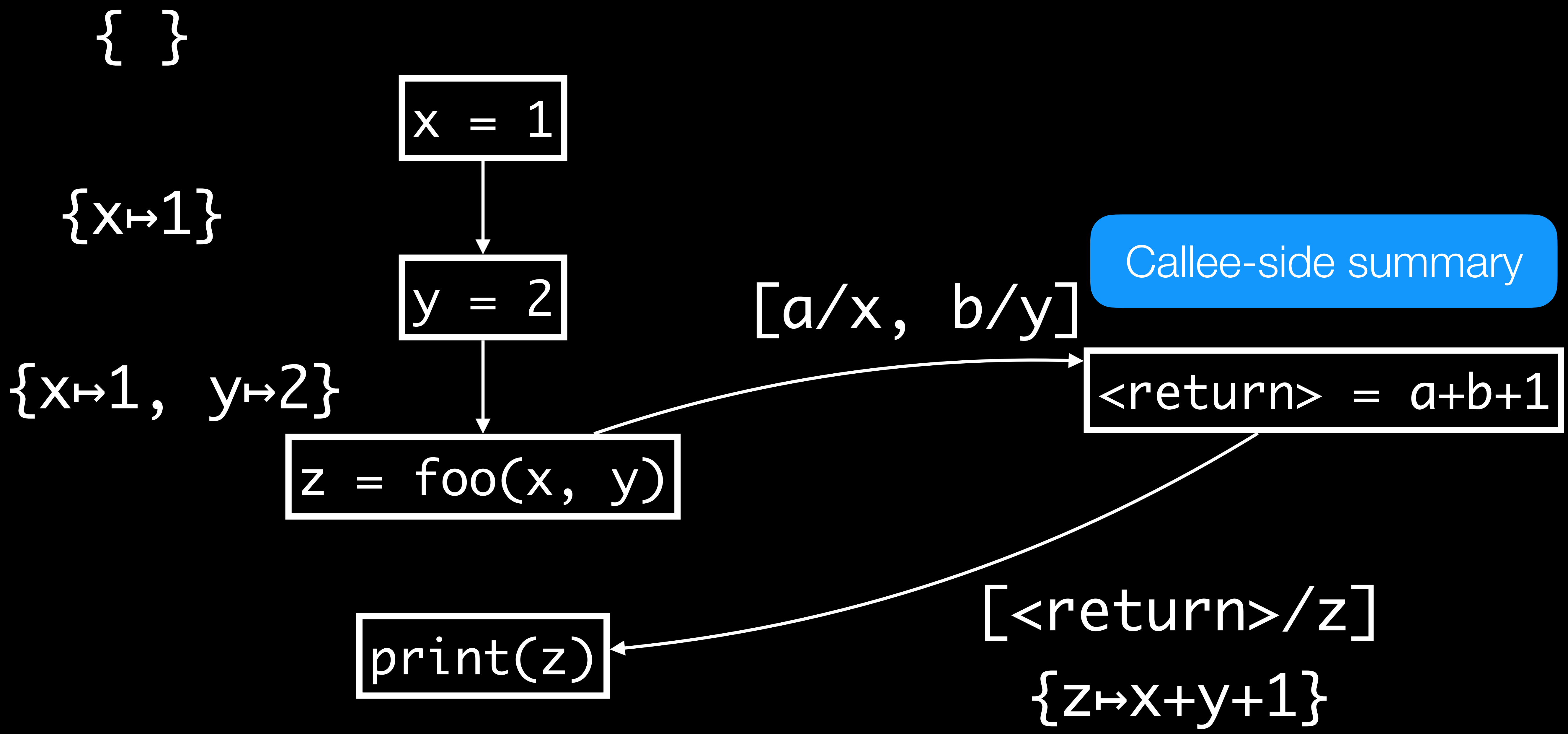
Callee-side summary

<return> = a+b+1

[<return>/z]

print(z)

# Functional Approach
# Example: Constant Propagation



{ }

x = 1

{x↦1}

y = 2

{x↦1, y↦2}

z = foo(x, y)

[a/x, b/y]

Callee-side summary

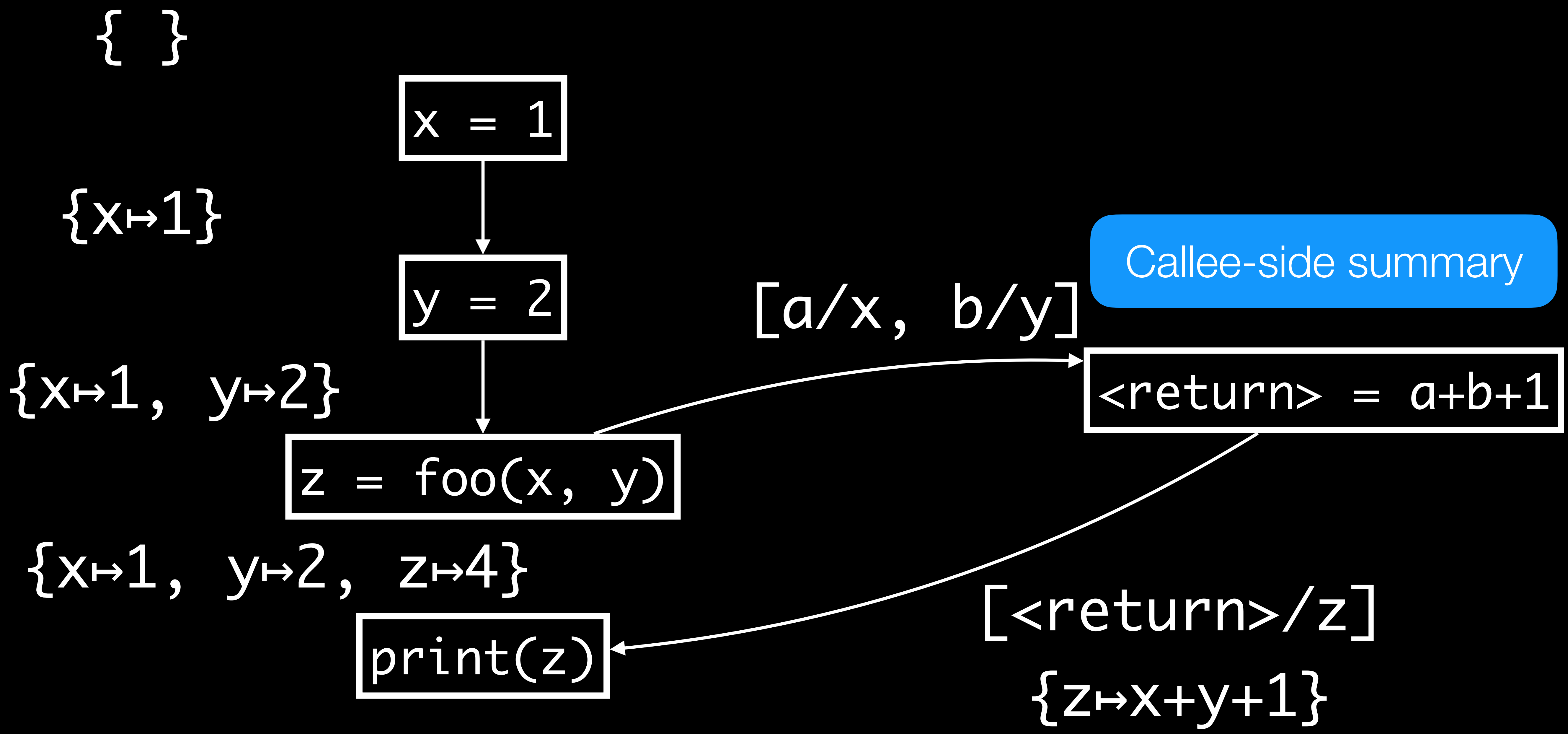
<return> = a+b+1

[<return>/z]

{z↦x+y+1}

print(z)

# Functional Approach
# Example: Constant Propagation



{ }

x = 1

{x↦1}

y = 2

{x↦1, y↦2}

z = foo(x, y)

{x↦1, y↦2, z↦4}

print(z)

[a/x, b/y]

Callee-side summary

<return> = a+b+1

[<return>/z]

{z↦x+y+1}

# Next

- IFDS